THE UNIVERSITY OF QUEENSLAND

AUSTRALIA

A treatise on the productivity of semi-automated pivot push bulldozing

Richard Kurt Hensel

B. E. (Mechanical) (Hons)

A thesis submitted for the degree of Master of Philosophy at
The University of Queensland in 2019
School of Mechanical & Mining Engineering

Abstract

Pivot push bulldozing is an overburden removal method used in strip mining. A team of bulldozers work in parallel slots to remove blasted earth material from above a coal seam, depositing into the previously-mined void adjacent to it.

This thesis occurs within a larger collaboration between the University of Queensland and Caterpillar Inc. which aims to automate the bulldozers which complete pivot push. The focus of the thesis is understanding the productivity of pivot push bulldozing, and how pivot push should most productively be automated. Initial investigation determined that pivot push productivity measurement would necessarily be based on simulation due to a large number of uncontrollable variables associated with direct experimentation. The thesis aims are; (i) validate a simulation framework for predicting the productivity of pivot push; (ii) use the validated simulation framework to identify how pivot push is most productively executed; and (iii) evaluate the performance of semi-automated pivot push bulldozing using the simulation framework to compare actual performance to expected performance.

Concurrently with the work of this thesis, a bulldozer simulation framework has been developed at the University of Queensland. The simulation framework generates the cuts and pushes required to move material into the void following the specified method. The first aim was addressed by way of an experimental trial which validated the predictions of the simulation framework by comparison with the data obtained.

The work towards the second aim was to use the validated simulation framework to compare the productivity of three methods for a range of strip geometries. The productivity of pivot push is subject to the geometry of the strip in which a bulldozer works as this influences the range of distances and grades at which the bulldozer must travel. It was found that the dumping tactics of TipHeadLevel and BackStackUphill resulted in the greatest overall productivity within the range of strip geometries which were tested.

The third aim was addressed through an experimental trial which compared the productivity and utilization of the semi-autonomous system against manual operation. It was found that SATS was less productive than expected when measured by the rate of material movement per hour. The increased complexity of the system and operator inexperience also led to a lower than expected portion of the bulldozer's time spent in effective effort. This investigation identified several issues with the current implementation so that future efforts can be focused on improvement.

The significance of this project is the evidence-based arguments around how pivot push should most productively be implemented. Further work aims to make system improvements based upon the findings presented here.

Declaration by Author

This thesis is composed of my original work, and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution by others to jointly-authored works that I have included in my thesis.

I have clearly stated the contribution of others to my thesis as a whole, including statistical assistance, survey design, data analysis, significant technical procedures, professional editorial advice, financial support and any other original research work used or reported in my thesis. The content of my thesis is the result of work I have carried out since the commencement of my higher degree by research candidature and does not include a substantial part of work that has been submitted to qualify for the award of any other degree or diploma in any university or other tertiary institution. I have clearly stated which parts of my thesis, if any, have been submitted to qualify for another award.

I acknowledge that an electronic copy of my thesis must be lodged with the University Library and, subject to the policy and procedures of The University of Queensland, the thesis be made available for research and study in accordance with the Copyright Act 1968 unless a period of embargo has been approved by the Dean of the Graduate School.

I acknowledge that copyright of all material contained in my thesis resides with the copyright holder(s) of that material. Where appropriate I have obtained copyright permission from the copyright holder to reproduce material in this thesis and have sought permission from co-authors for any jointly authored works included in the thesis.

Publications included in this thesis

R. Hensel, T. Cullen, P.R. McAree, D. Medland, M. Addley, S. Mumford, and K Austin (2017) Bulldozer Pivot Push Use Case Document. Technical report, The University of Queensland - School of Mechanical & Mining Engineering - Incorporated as Appendix A

Submitted manuscripts included in this thesis

No manuscripts submitted for publication.

Other publications during candidature

Technical reports

R. Hensel, Z. Smith, K. Austin, K. Choros, and P.R. McAree (2017) Semi-autonomous tractor productivity under pivot push: methodology and productivity evaluation. Technical report, The University of Queensland - School of Mechanical & Mining Engineering

R. Hensel, T. Cullen, P.R. McAree, D. Medland, M. Addley, S.Mumford, and K Austin (2017) Bulldozer Pivot Push Use Case Document. Technical report, The University of Queensland - School of Mechanical & Mining Engineering

Contributions by others to the thesis

The candidate was assisted by colleagues and supported by projects in the Smart Machines Group at the University of Queensland. The work presented in the thesis has been the candidate's own work.

The descriptions of pivot push bulldozing in Chapter 1 are based upon the work included as appendix A. The document in appendix A was developed through consultation with David Medland (Medland Mining Services) and with production supervisors Matt Addley and Sean Mumford employed by Peabody Energy Australia at Wilpinjong Mine. Tim Cullen, Ross McAree and Kevin Austin assisted in the initial information gathering and drafting of this document, after which several revised versions, including the final version included here were created by the candidate.

The pivot push simulation framework was developed primarily by Zane Smith within the Smart Machines Group along with assistance from the candidate and other colleagues including Sam Bettens.

The experimental data used in Chapters 2 and 4 was gathered at Wilpinjong mine under experiments designed and executed by the candidate, and made possible by investments of time and resources from Peabody and Caterpillar.

Statement of parts of the thesis submitted to qualify for the award of another degree

No works submitted towards another degree have been included in this thesis.

Research Involving Human or Animal Subjects

No animal or human subjects were involved in this research.

Acknowledgements

First and foremost, thanks to Ross McAree my supervisor. Ross has challenged me to learn and improve by only ever asking for my best. Ross is infamous for his lack of free time, and I feel I have only accentuated this phenomenon over the past few months. A large amount of whatever time remained, he has spent on this thesis. For this and everything else I am very grateful.

Thanks to the guys at the Smart Machines Group for their contribution to the project, help with my work and for being general good sorts. Zane Smith, our very own resident C++ wizard developed the bulk of the simulation tools used in this thesis (among many other things) and Sam Bettens did great work on the pushable volumes component of that simulation. The validation trial was much more enjoyable thanks to Felipe Donoso, who accompanied me to site and assisted with the early analysis of data. Thanks to Tim Cullen for his assistance in the initial stages of the project which ended up becoming the document attached as Appendix A. Many thanks also to Kevin Austin for his trademark thorough consideration and sound advice.

To the guys at Caterpillar, thanks for the opportunity to work on this project and for the mentoring I've recieved along the way. Nigel Boswell kept everything moving, while providing constant amusement to all nearby. Peter Beasley set everything up, fixed it when it broke, showed me how it is done, and answered a whole lot of questions.

At Wilpinjong, the experimental components of this thesis could not have been completed without the help of Matt Addley, Sean Mumford, Will Heesterman, Matt Brown, Grant Stephens, Notty, all of the SATS operators and many others. I have immense respect for these people who were willing to go out of their way to help with the multitude of extraneous requests I had throughout the course of these trials. This was all enabled by the great leadership of Blair Jackson and Peter Grosvenor who got right behind the project, and were patient whenever issues emerged.

Finally, thankyou to my family who have always been there to support me.

Financial support

The work of this thesis was funded by the Australian Coal Association Research Program (ACARP) as part of a research project entitled ‘Automated bulk dozer push: reducing the cost of overburden removal’.

Indirect in-kind support such as technical support and access to testing areas were provided by Caterpillar Inc. and Peabody Energy.

Keywords

mining automation, bulldozer, dozer push, simulation, productivity

Australian and New Zealand Standard Research Classifications (ANZSRC)

ANZSRC code: 091302, Automation and Control Engineering, 100%

Fields of Research (FoR) Classification

FoR code: 0913, Mechanical Engineering, 100%

Table of Contents

List of Figures

List of Tables

List of Abbreviations

1R	First gear reverse
2R	Second gear reverse
CDX	Cast, Doze, Excavate
Dozer	Track-type tractor bulldozer
GNSS	Global Navigation Satellite Solution
IMU	Inertial Measurement Unit
RTK	Real Time Kinematic
SATS	Semi Autonomous Tractor System
UAV	Un-manned Aerial Vehicle

CHAPTER 1

Pivot push bulldozing

Not just a machine;
large, yellow, autonomous.
That sounds pretty cool.

Thesis scope and objectives

This thesis studies the semi-automation of bulldozers used in an earth moving method commonly known as pivot push bulldozing. Pivot push is generally conducted as the second phase of a strip mining process called cast-doze-excavate (CDX) [Dyer and Hill, 2011] of which the workflow is illustrated in Fig. 1.1.

The first phase of CDX involves the use of explosives to fragment the rock (*overburden*) above a coal seam and cast a portion of it into the void left when the adjacent strip was mined [Dyer and Hill, 2011], see Fig. 1.1(b).

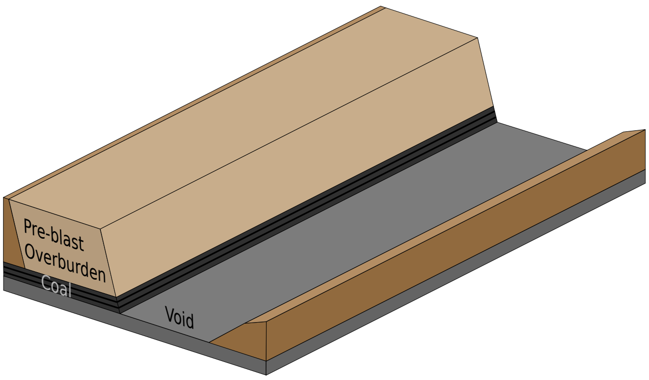
Pivot push is executed as the second phase of CDX by a team of bulldozers that systematically push the remaining blasted overburden until the void is filled. [Hayes, 1997], see Fig. 1.1(c). Pivot push is an efficient method for earth moving, particularly in the early stages where the bulldozer's efforts are aided by gravity [Lucas and Siddig Kizil, 2014]. However, as the void fills, the bulldozers must push their loads further, and eventually push them uphill, with the cost of material handling ever-increasing.

The third phase of CDX uses excavators and trucks to move the remaining material and continues until coal is exposed, see Fig. 1.1(d). This phase is planned to commence when the cost-per-unit of material moved by pivot push exceeds the cost of doing the same work using an excavator.

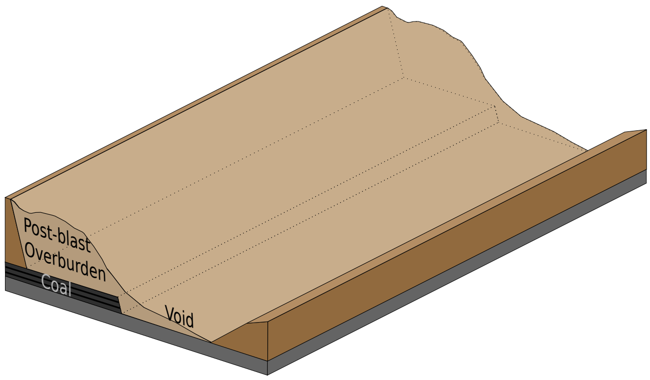
The broad objectives of this thesis are to understand how pivot push can be automated and to evaluate the productivity of a semi-autonomous bulldozer performing pivot push. The work forms part of a larger collaboration between Caterpillar Inc. and The University of Queensland and builds on the Caterpillar Command-for-Dozing technology [Caterpillar, 2012].

The aims of this thesis are:

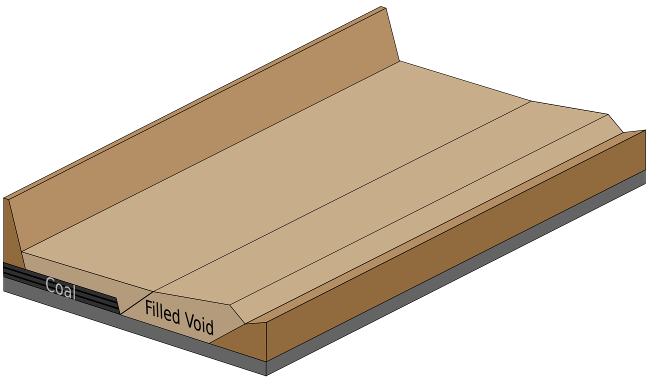
1. validate a simulation framework for predicting the productivity of pivot push;
2. use the validated simulation framework to identify how pivot push is most productively executed; and
3. evaluate the performance of semi-automated pivot push bulldozing using the simulation framework to compare actual performance to expected performance.



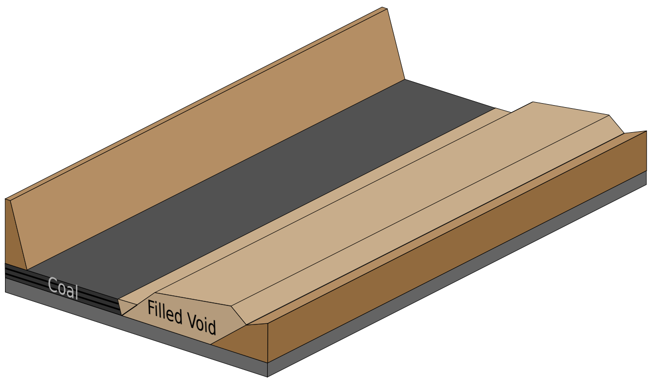
(a) The strip before blasting. The overburden lies in a contiguous block directly above the coal seam and a void remains following mining of the previous strip.



(b) The strip after blasting. Some of the overburden, now fragmented, has been cast into the void by the energy of the blast. Pivot push begins from this state.



(c) The strip after pivot push is completed. The void has been filled to capacity. Remaining overburden must be removed by excavator.



(d) The strip after the excavator has removed all remaining material above coal.

Figure 1.1: A three-dimensional view of a strip at key stages as it is worked by CDX.

Aim 1: Validate a simulation framework for predicting pivot push productivity

This aim is motivated by the simple fact there is no established validated method to predict the productivity of pivot push bulldozing.

Methods in general use for predicting bulldozer productivity such as [Uren and Nehring, 2015; MECMining, 2015] are based on manufacturer production curves presented in [Caterpillar, 2010]. For a given model of bulldozer, these curves provide the maximum uncorrected productivity in units of loose cubic meters per hour as a function of push distance. Correction factors are applied to account for operator skill, the characteristics of the material being handled, bulldozer blade capacity and grade. These methods are currently the best available for mine designers planning a pivot push operation.

Other methods such as [Klanfar et al., 2014; Tsuji et al., 2011; Xia, 2009] make some attempt to model the interaction of the blade with the terrain over which the bulldozer passes. These methods make use of blade volume heuristics based on simplifying assumptions of bulldozing grade and blade geometry.

These existing approaches take no consideration of some key specifics of the material movement problem, including the movement that occurs solely due to gravity, and the limitations in tractive effort the bulldozer may exert to push the load of material.

The starting point of this thesis is the assertion that the productivity of pivot push bulldozing (and bulldozer operations generally) cannot be considered in the abstract and must necessarily take into consideration the context in which they are executed. Elements of this context include the strip geometry as defined by the post-blast terrain, the strip plan defining the material to be moved, and the properties of the material that must handled. A strip that is easily pushed because, for example, the geometry is favourable should be identified as such in any prediction of pivot push effectiveness. Similar considerations apply for a strip with a less favourable geometry.

The first aim of this thesis is to validate the pivot push simulation framework described in Hensel et al. [2017]. This simulation framework has been developed as a part of the larger project under which this thesis has been conducted. The framework is able to simulate the bulldozer actions necessary to move material from an initial terrain to a specified final design geometry. A material model simulates the movement of material under these actions. The simulation framework maintains records of volume moved and time spent in productive effort so that the overall productivity of the operation can be computed.

The simulation framework is validated by an experimental trial. Material volume moved, measured by aerial survey, is compared with predictions at various points in the trial to determine the degree to which they are correlated.

Aim 2: How to most productively execute pivot push bulldozing

The second aim of this thesis is to determine how best to choreograph the sequence of cuts and pushes a bulldozer should undertake when completing pivot push. There are differing schools of thought in the industry [MECMining, 2015; Medland, 2015; Nott, 2015] on how best to pivot push, but little in the way of hard evidence for preferring one method over others. It is reasonable to expect, nevertheless, that some approaches are more efficient than others and, that different methods may be preferred in different circumstances.

The thesis explores the question of how best to pivot push by comparing the predicted productivity of three commonly used pivot push methods on a trial strip to determine which is most productive. This capability is used to inform the decision of which pivot push method to implement for semi-autonomous pivot push bulldozing.

Aim 3: Evaluate the performance of semi-automated pivot push

The third aim of the thesis is to evaluate the performance of a semi-autonomous system using the preferred pivot push method identified at Aim 2. The methodology used to address this aim involves the comparison of predicted material volume movement rates with measured rates obtained by aerial survey. A manual operation executed alongside the autonomous operation serves as a control for this comparison.

The outcome of the third aim is an understanding of the performance of semi-autonomous pivot push bulldozing and the identification of opportunities for improvement.

Basic bulldozer operation

Figure 1.2 depicts a Caterpillar D11T track-type tractor or bulldozer, designed for short-range bulk earth moving operations [Martin et al., 1982]. The D11T can push up to 60-cubic-metre loads of fragmented earth material up to distances of 150 metres [Caterpillar, 2001]. The machine typically operates at speeds of 1 m/s when loaded and 2 m/s unloaded [Berkhimer, 2011].

The main components of the bulldozer are:
Operator Cabin: Houses the operator and all control interfaces. Limited forward vision of the blade is available from the cabin.

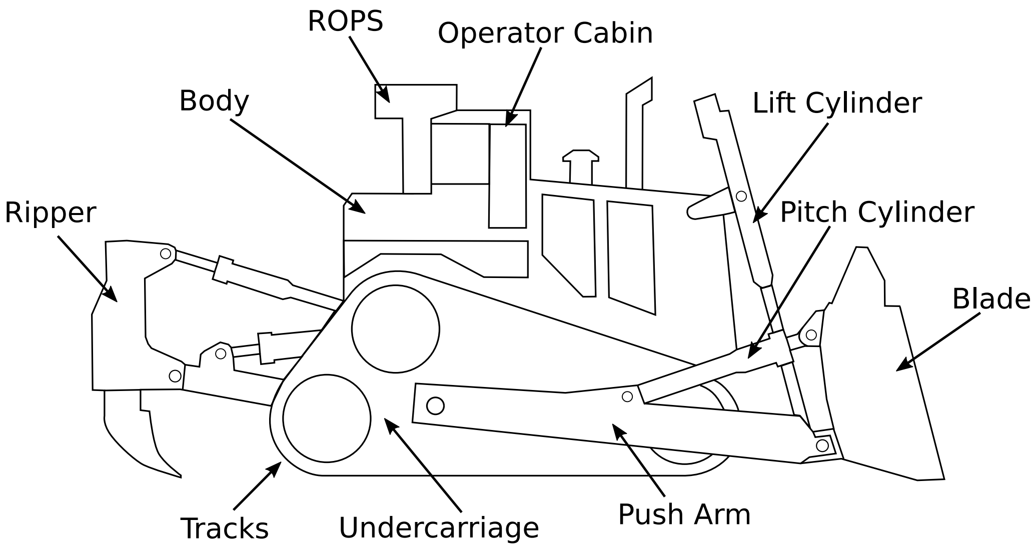


Figure 1.2: The Caterpillar D11T bulldozer.

ROPS: Roll-over protection structure.

Body: Includes the engine bay, powertrain and structural components of the machine.

Undercarriage: The structure and rolling gear around which the tracks rotate while travelling.

Tracks: Crawler-tractor tracks featuring robust grousers.

Push Arm: The force carrying link between the blade and the body of the machine. The push arms pivot about their mounting point on the undercarriage as the blade is raised and lowered.

Blade: The primary ground engaging tool of the machine. The blade is sized according to the power of the machine.

Pitch Cyclinder: Mounted to the push arm, providing the ability to pitch the blade forwards and backwards.

Lift Cylinder: Mounted at the front of the body, controlling the elevation of the blade.

Ripper: The secondary ground engaging tool mounted to the rear of the body. The ripper is primarily used to fragment material to be more easily worked with the blade.

Slot bulldozing

The material movement of pivot push is achieved by slot bulldozing, wherein the bulldozer repeatedly pushes material along a linear *slot*. Pushing consecutive loads along a slot creates a wall on either side of the blade, preventing material spillage on future passes [U.S. Army, 2000]. In pivot push bulldozing, many parallel slots are created side-by-side along the length of the strip. The slots are aligned perpendicular to the strip, and bulldozers orient themselves to push material along the slot towards the void.

Slot bulldozing consists of many repeating *cycles* of operation. A slot bulldozing cycle (see Figs. 1.3 and 1.4) consists of a cut to fill the blade, a carry where the loaded material is pushed along the slot floor without acquiring new material, and a return pass where the machine reverses unloaded, usually as fast as practicable, to the next cutting location. The transition from a forward-travelling carry to the reversing return dumps material and this is sometimes accompanied by a slight raise of the blade to encourage material to remain. When ground material is hard or compacted, it may be necessary to perform a ripping pass, where the ripper is lowered and dragged through the slot floor during forward travel to loosen the material so that it is easier to cut [Dyer and Hill, 2011].

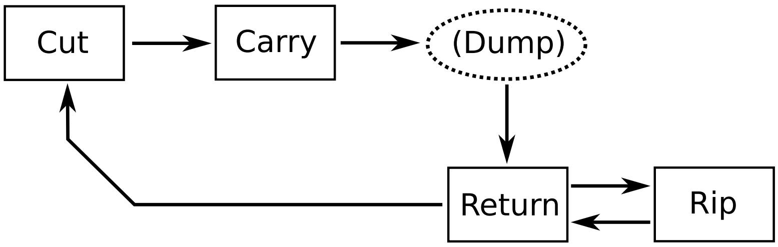


Figure 1.3: Basic slot bulldozing cycle breakdown.

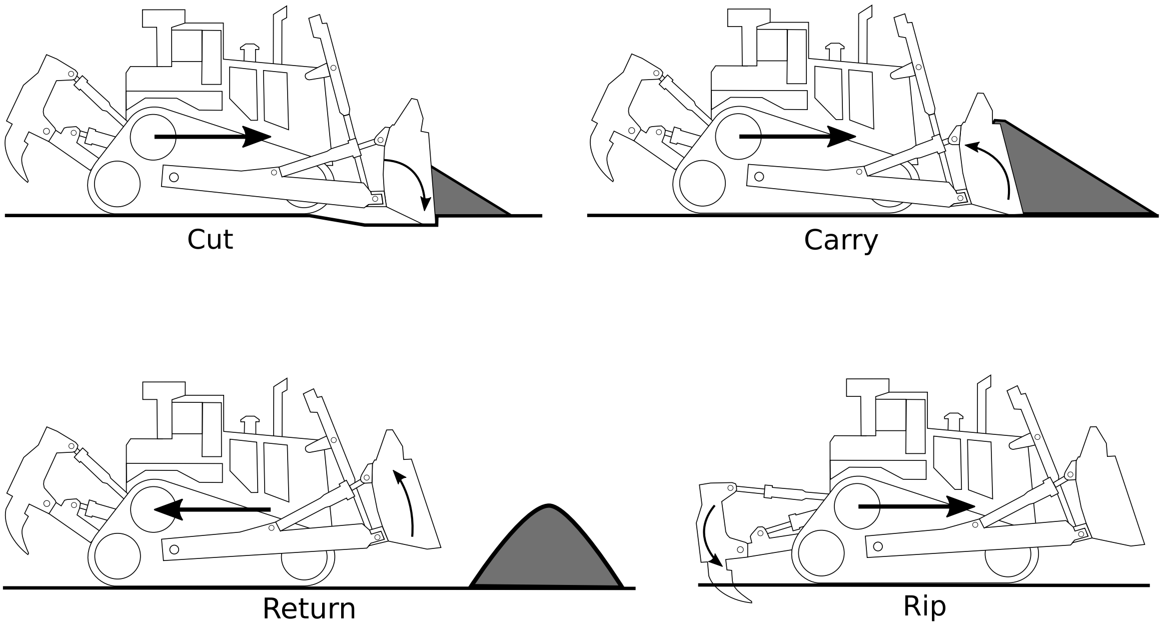


Figure 1.4: A visual representation of the key activities in a slot bulldozing cycle.

In an effort to maximize productive output, bulldozers are worked at the limits of their capability. Cutting is executed aggressively so that the blade is filled in the shortest possible distance [Medland, 2015]. During carrying the aim is to maximize tractive power which is function of blade load, travel speed, and ground conditions [Davidson et al., 1935; Garber, 1985]. The return is made as quickly as possible, however due to whole-body vibration levels increasing with velocity, is limited to the comfort of the operator [Pope et al., 2002].

The operator controls the machine largely on feel and experience. The process of acquiring and maintaining a blade load during the cut and carry is done by sensing the movement of the machine and listening for the effort exerted by the engine. The positioning and orientation of the blade must be constantly adjusted to maintain the ideal load so that the full available engine power is utilized but is not so great that the machine loses traction [Macmillan, 2002].

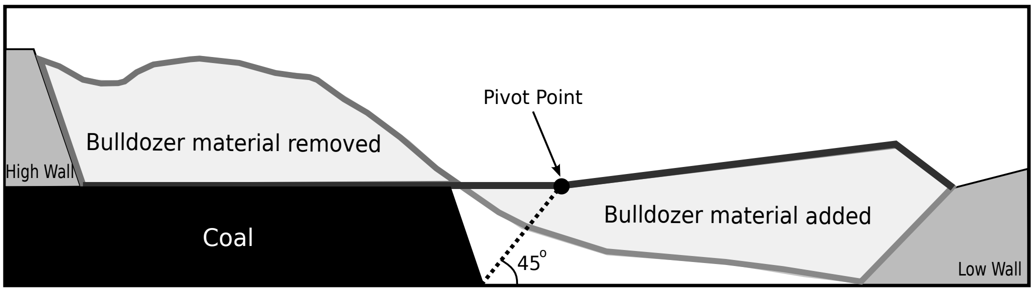
Bulk overburden removal by pivot push bulldozing

Pivot push is a strip mining overburden removal process where a team of bulldozers moves material from above a coal seam through a sequence of choreographed cuts, carries, and dumps. Pivot push bulldozing commences after explosive charges are used to fragment material above the coal seam and cast a portion of it into the void remaining from the previous strip that was mined (see Fig. 1.1). Pivot push bulldozing achieves its economies by employing a highly structured movement method. This section summarizes the actions and tactics which constitute a pivot push method. A detailed description of pivot push bulldozing, including variations that arise, can be found in Appendix A.

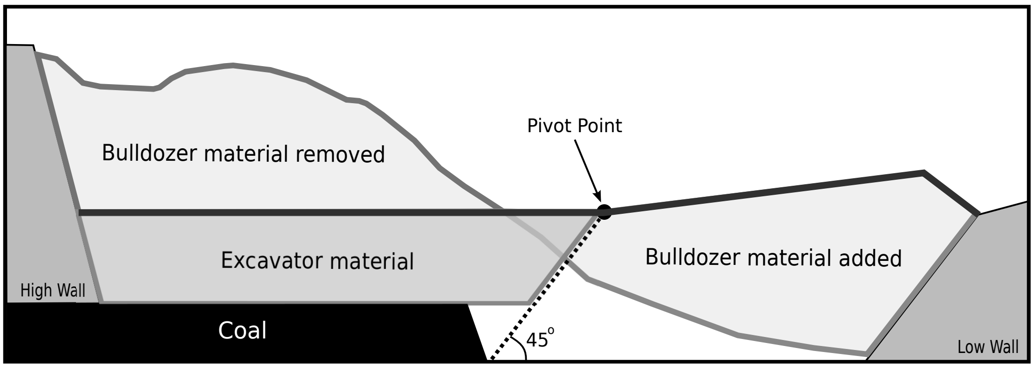
Planning

Pivot push bulldozing is executed according to a high level plan which is designed to achieve the most cost effective use of bulldozers. The plan specifies the final terrain of the strip following pivot push.

The productivity of bulldozers is strongly dependant on the distance and grade of travel between the cutting and dumping locations [Caterpillar, 2010]. The distance of travel, grade of travel and per-volume cost all increase throughout the operation. It is common at some point in the operation for it to become cheaper to continue with another method, e.g. an excavator loading trucks. This typically occurs once it becomes necessary to push material at an uphill grade once the void has been filled. As illustrated in Fig. 1.5, the relative heights of overburden and coal seam will determine the point at which the void is filled, and pivot push ceases.



(a) Cross-section view of pivot push geometry of a shallow mining operation.

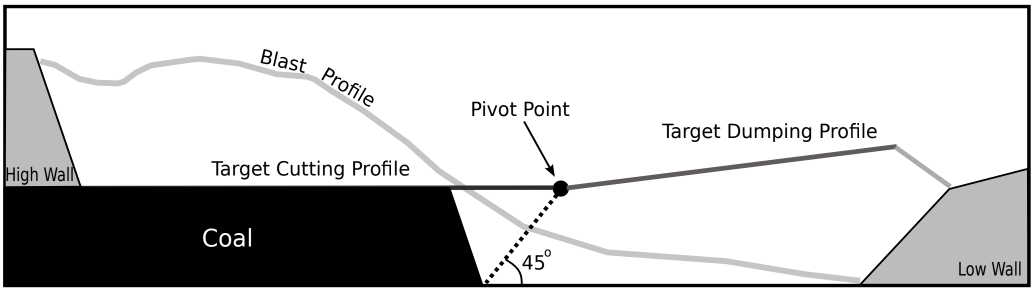


(b) Cross-section view of pivot push geometry in a deep mining operation.

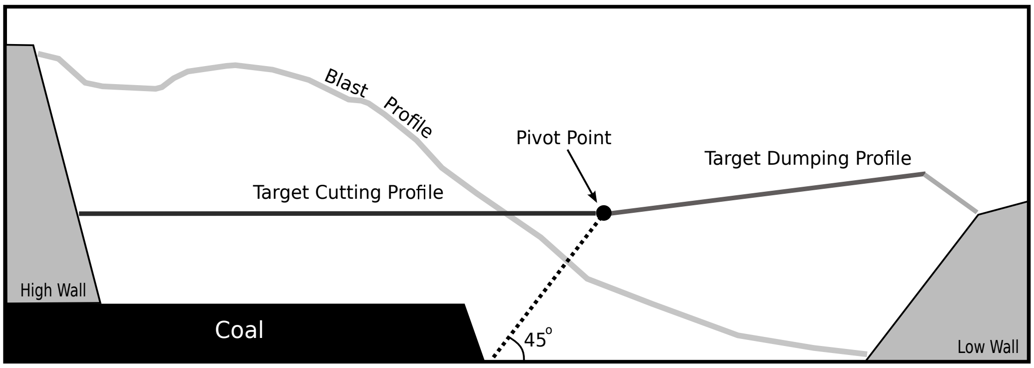
Figure 1.5: In example (a), The overburden is shallow enough that all material is able to be moved into the void with bulldozers. In example (b), the overburden is too deep for all material to be moved into the void using bulldozers. The remaining material must be removed by excavator following the completion of pivot push.

The planning process is aided by productivity models which estimate the economic limits of pivot push. Existing models compute a productivity estimate based on the distance and grade of a hypothetical line connecting the centroids of material before and after it has been moved [Caterpillar, 2010]. The per-hour cost of operation is known to a reasonable precision for both bulldozers and excavators, therefore, the transition point is where the cost to move the material with bulldozers exceeds that of excavators. In reality, this transition point is often determined through 'rules of thumb', whereby the bulldozer operation should cease when the dump profile above the void has reached an uphill grade of 20% and extends across the void to intersect the top of the low wall [Nott, 2015].

It is common that the plan is generated as a 3D surface representing the desired final terrain. Implicit in the plan is the target cutting profile, target dumping profile, and the pivot point, see Fig. 1.6. Fleet management systems used in modern operations such as Leica Jigsaw [Leica-Geosystems, 2013] and Caterpillar MineStar [Caterpillar, 2012], guide supervisors and operators through a graphical interface that indicates the position of the machine in the strip and whether it should be cutting or filling at that location.



(a) Planning pivot push in a shallow mining operation.



(b) Planning pivot push in a deep mining operation.

Figure 1.6: The pivot push plan includes the target cutting profile, target cutting profile and pivot point.

Target Cutting Profile

The Target Cutting Profile represents the desired geometry of the overburden region following the completion of the bulldozer operation. The target cutting profile is generally a horizontal plane, either on or at an offset above the top of coal.

Target Dumping Profile

The Target Dumping Profile represents the desired final geometry of the material which has been pushed into and stacked above the void. It is seen as best practice that the dump profile should not be steeper than a grade of 20% uphill above the void.

The Pivot Point

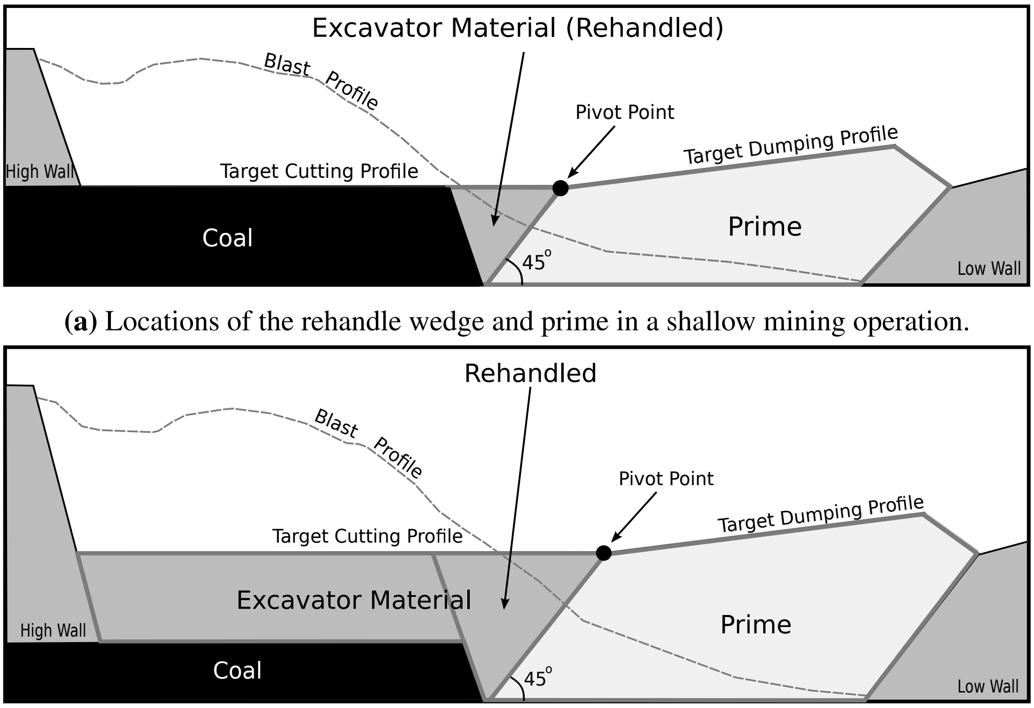
The pivot point is the notional point on any cross section at the intersection of the target cutting profile and a line emanating from the bottom of the coal seam within the void at a specified angle, usually 45 degrees, see Fig. 1.7. The pushes can be thought of as pivoting around the pivot point with the pivot point marking the division between cutting and dumping.

The material indicated in Fig. 1.7 as *rehandled* constitutes a wedge between the coal toe and the target cutting profile. This material is placed in part by the blast and in part by bulldozers. The wedge must be removed by excavator following pivot push to provide access to the coal. The angle of the line on which the pivot point is inscribed is usually 45 degrees, as it is approximately equal to the angle at which the material will support itself once the adjacent material has been removed by an excavator.

Prime

Material which has been successfully moved into the void, and will not need to be moved again is said to be at *prime* [Shonts and Nettleton, 2011]. The prime region is defined by the geometry of the strip and design profiles, shown in Fig. 1.7. In this cross section, the prime region is bounded by the line which passes from the bottom of the coal void face to the pivot point.

In the chapters that follow, the calculation of productivity considers only material volume which has been moved to the prime region. Movement of material which does not eventuate at prime, or movement of material which is already located at prime is not seen as productive.



(a) Locations of the rehandle wedge and prime in a shallow mining operation.

(b) Locations of the rehandle wedge and prime in a deep mining operation.

Figure 1.7: Any material not placed into the region designated as *prime* must be removed by excavator following the completion of pivot push.

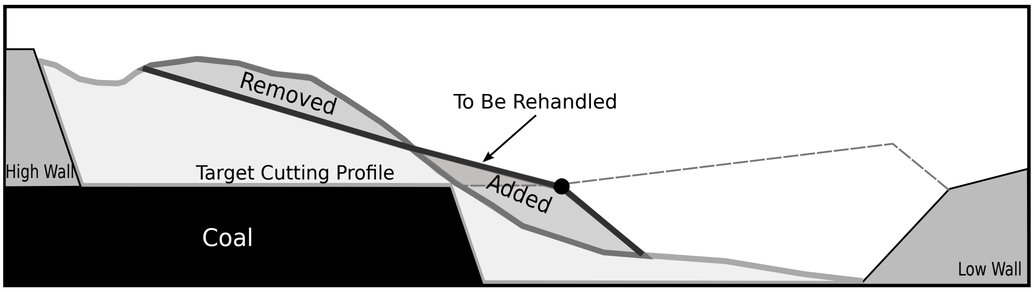
Preparation

Preparation tactics ensure that the terrain geometry is suitable for productive slot bulldozing. Preparation tactics involve using bulldozers to smooth the rough terrain created by the blast, create slots, and establish a working grade which enables access to the pivot point.

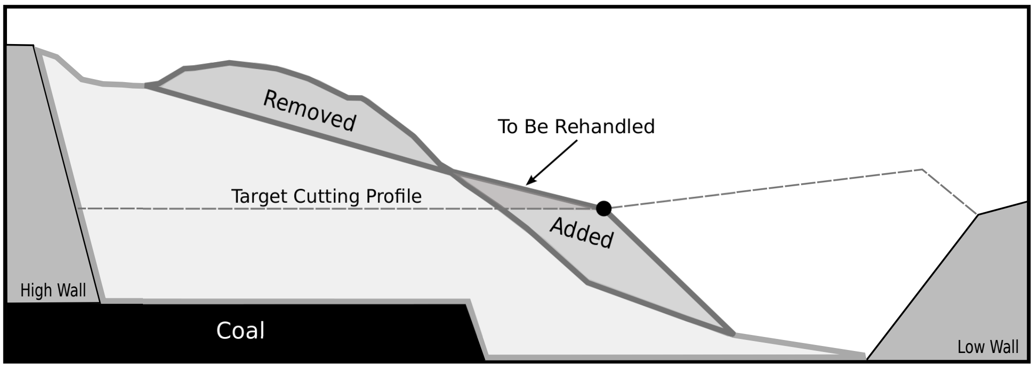
Establish Working Grade

The first operation stage enables prime dumping to commence by establishing a working grade to the pivot point see Fig. 1.8. The working grade is essentially a ramp extending from the top of the blast profile to the pivot point, allowing the machine to easily traverse this distance in future cycles. If the bulldozer were to attempt to move material directly to prime without first establishing this grade, it would travel down a gradient too steep to be traversed in reverse. The working grade is typically $25\% \pm 5\%$.

A portion of the material which is moved whilst establishing the working grade must be later rehandled. As shown in Fig. 1.8, material which rests above the target cutting profile will be rehandled during the following stages of pivot push. Pushing downhill at a steeper grade will reduce the amount of material which must be rehandled in the process, although this comes at the expense of reduced reversing velocity and increased wear on the machine.



(a) Establish Working Grade in a shallow mining operation.



(b) Establish Working Grade in a deep mining operation.

Figure 1.8: A working grade intersecting the pivot point is established. Some of the material is temporarily placed above the target cutting profile and will be rehandled in later stages of the pivot push operation.

Prime Production

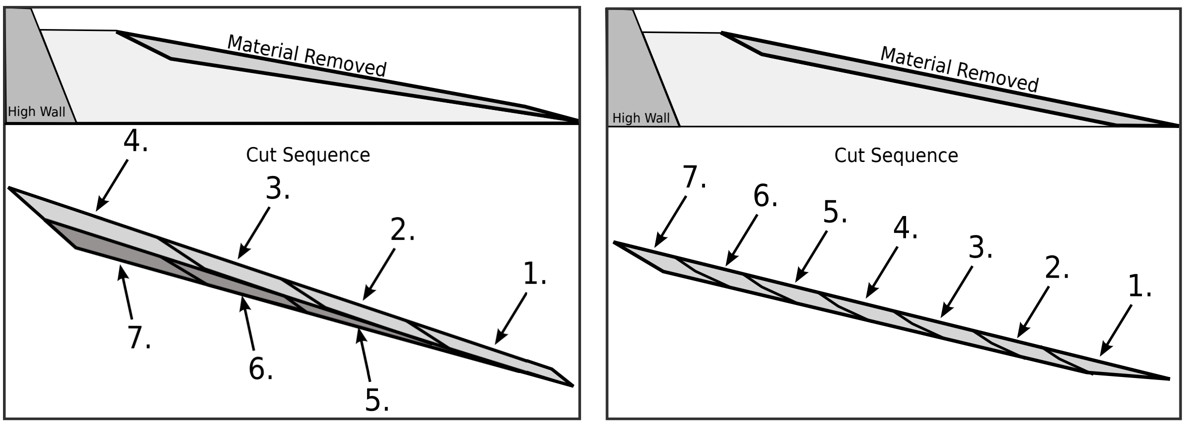
Prime production constitutes the majority of the pivot push operation. In this phase, the bulldozer moves material from above the coal seam to a prime location. There are several alternative tactics by which material may be moved. All tactics share the same common elementary operation of slot bulldozing but differ in their sequencing of cutting and dumping locations.

The cutting and dumping processes can be considered as concurrent but decoupled operations. The decision of where to cut is only dependant on the current geometry of the cutting region and likewise the decision of where to dump is only dependant on the geometry of the dumping region. The cutting and dumping tactics do not influence each other.

Cutting Tactics

Cutting tactics subtractively transform the geometry of the overburden region to reach the target cutting profile. Two tactics are favoured, differing in the shape and grade of the terrain profile created during intermediate steps. The two alternative cutting tactics are *Progressive Grade Cutting* and *Constant Grade Cutting*.

Progressive Grade Cutting removes material while reducing the grade of the top surface from the initial working grade to horizontal as seen in Fig. 1.9.



(a) Progressive Grade Cutting. **(b)** Constant Grade Cutting.

Figure 1.9: Cutting tactics.

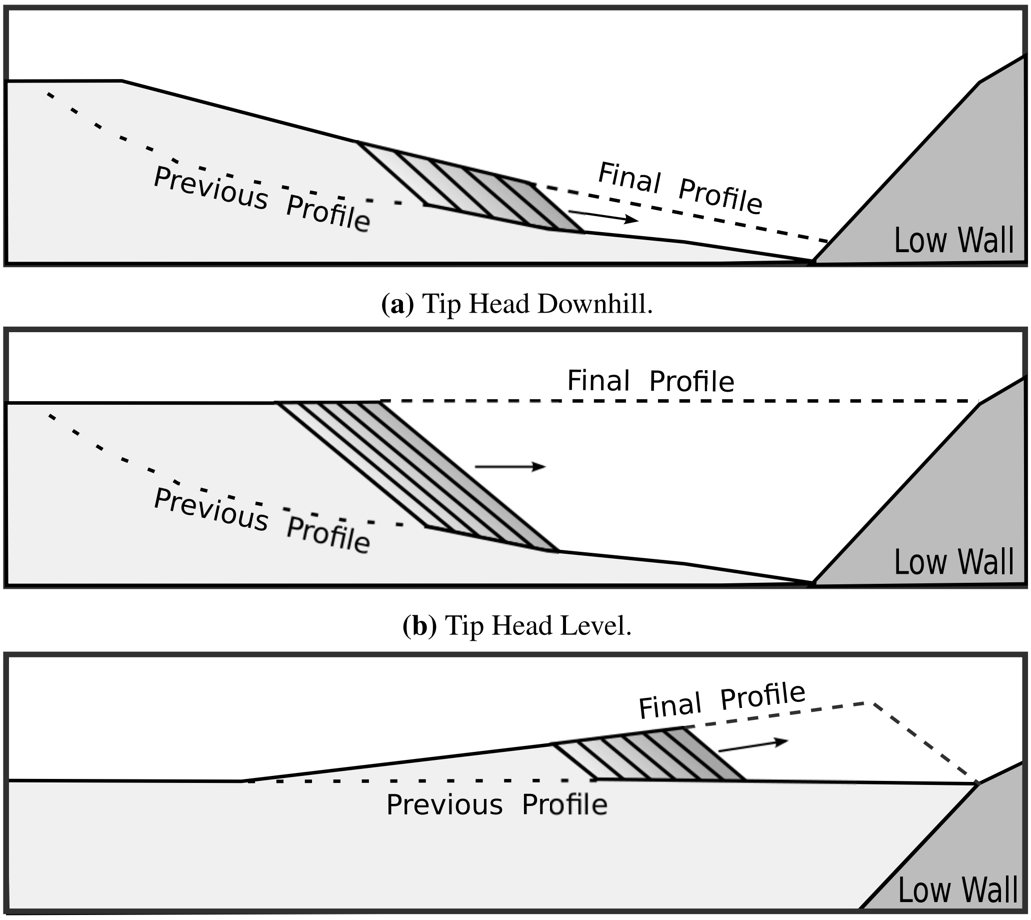
Constant Grade Cutting removes material while maintaining the grade of the top surface at the same initial grade as seen in Fig. 1.9. This tactic requires material to be carried downhill from the cutting location and level across the target cutting profile.

Dumping Tactics

Dumping tactics additively transform the geometry of the void region until the target dumping profile is reached. There are several alternative dumping tactics which differ in the geometry of the intermediate profiles and in the sequencing of dump locations. The dumping tactic often changes several times throughout the prime production phase of pivot push as the geometry of the void region evolves.

Tip Heading and *Back Stacking* are the two basic dumping methods with each having different variants.

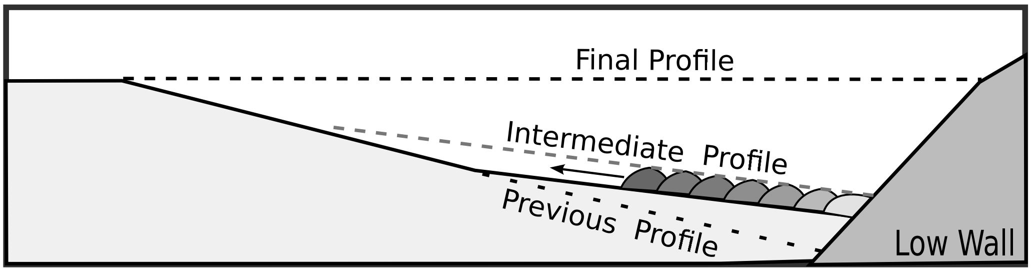
Tip Heading (see Fig. 1.10) is a dumping tactic in which loads of material are pushed to a steep edge and allowed to fall into the void, forming at the natural angle of repose of the material. The notional front face of the tip heading profile gradually advances further into the void with each dump. The tip heading profile may be advanced at any grade as specified by the design. Tip Heading Downhill is used in preparation for Back Stacking Downhill, creating a downhill grade which can then be stacked on top of. Tip Heading level is used to entirely fill the capacity of the void below the plane of the target cutting profile. Tip Heading Uphill is used for filling above the plane of the target cutting profile.



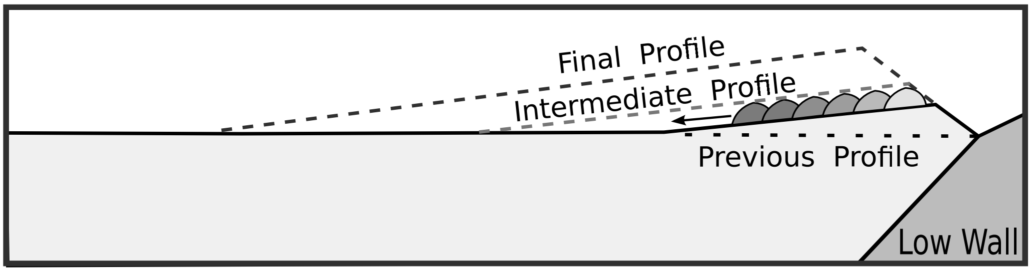
(c) Tip Head Uphill.

Figure 1.10: Tip Head dumping tactics. The front face of the tip head profile advances with each dump, as indicated by the direction of the arrow.

Back Stacking (see Figure 1.11) is a dumping tactic in which the dump region is filled with successive layers which are stacked directly into place. The tactic involves alternating tasks of *stacking* and *flattening*. Stacking moves the bulk of material, placing successive loads from the low wall side to the pivot point. Flattening creates a new floor on top of the previous stacks to allow new loads to be stacked above the previous. Back Stacking Downhill fills the void below the plane of the target cutting profile. Back Stacking Uphill fills above the plane of the target cutting profile.



(a) Back Stack Downhill.



(b) Back Stack Uphill.

Figure 1.11: Back Stack dumping tactics. This figure shows the tactic mid-way through one stacking task, where successive loads are placed incrementally as indicated by the direction of the arrow. Once the intermediate profile is filled, the tops of the current stacks are flattened, allowing the bulldozer to create a new level by stacking again from right to left.

Cleanup Operations

In certain circumstances, bulldozers must carefully scrape the remaining material from above the top of coal. Cleanup is required only if the plan dictates that bulldozers are to remove all material above the top of coal. This scenario arises in certain mining operations where the overburden is shallow and the void space large. The aim of cleanup is to minimize the amount of overburden material remaining while ensuring that the coal itself is undamaged.

Excavation at the highwall

When slot bulldozing, bulldozers are unable to remove the material within one bulldozer-length of the high wall while orientated towards the void. Bulldozers instead create a horizontal *bench* at the rear of each slot, and this material is periodically removed by an excavator. This practice leads to greater average productivity and lower cost per unit of material than the alternative strategy wherein bulldozers remove this material by cutting parallel to the highwall [Sinclair, 2016].

Figure 1.12 illustrates the movement of material by the high wall excavator. The high wall excavator completes periodic passes along the length of the high wall inside the strip, cutting material from the top of the excavator bench and dumping further into the strip. This material is then pushed away by bulldozers. Excavator passes are scheduled such that the elevation of the excavator bench reduces at a similar overall rate to that of the slot floor.

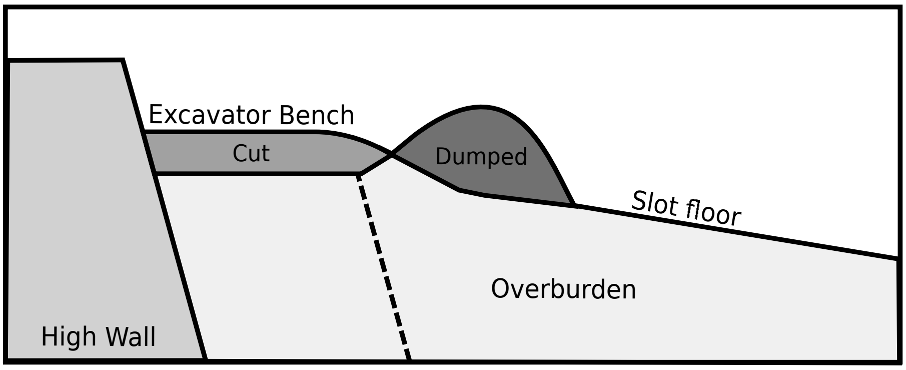


Figure 1.12: Material moved by the highwall excavator.

If the excavator bench is not worked synchronously with the rest of the strip, it may be necessary to delay the entire pivot push operation until an excavator pass has occurred. A large difference in elevation between the excavator bench and slot floor could constitute a risk to operational safety.

A grammar for pivot push

This section presents a framework for describing pivot push bulldozing and its variants using the Extended Backus-Naur Grammatical form. The purpose of this grammar is to give a precise description of pivot push bulldozing. For the purposes of this thesis it is used to both describe different methods of pivot push and as a means for specifying the method a semi-autonomous bulldozer might be commanded to execute.

This grammar has been developed by the author as an outcome of the effort to characterise the operation. Similarly to the use case document (Appendix A), this information was obtained through conversations with experienced bulldozer operators and supervisors, along with direct observations of prodction bulldozing on a mine site.

EBNF grammar preliminaries

The Extended Backus-Naur Form (EBNF) grammar notation allows for the definition of a set of semantic rules which control a language. It is commonly used in the development of programming languages, as well as in the specification of rules, document templates and protocols [Grune et al., 2012; Chang, 1983]. EBNF defines expressions through a series of equivalences. An expression is said to either be a ‘terminal’ representing a complete description or ‘non-terminal’ - which can be further decomposed into another set of expressions on a lower level.

EBNF typically follows a form such as:

```
<Non-Terminal> = "<Terminal>", "<Terminal>" | <Non-Terminal> ;
```

using the following symbols as ‘operators’:

- **=** Equivalence. Symbol to the left-hand-side is equivalent to the symbols on the right-hand-side.
- **;** Termination of line.
- **,** Concatenation (AND).
- **|** Alternation (OR).
- **[ ]** Optional.
- **{ }** Repeated.
- **( )** Grouping.
- **“ ”** Terminal String.

Scope

The grammar describes only pivot push bulldozing and does not extend to the operations which occur around it. This grammar describes preparation tactics, prime production tactics, and cleanup tactics.

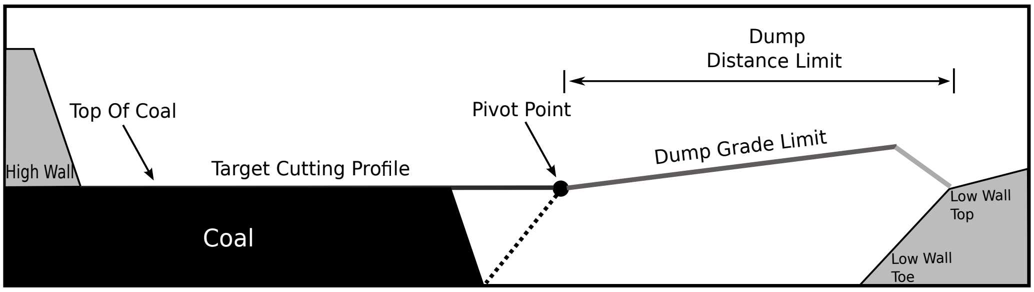
Definitions

Geometry

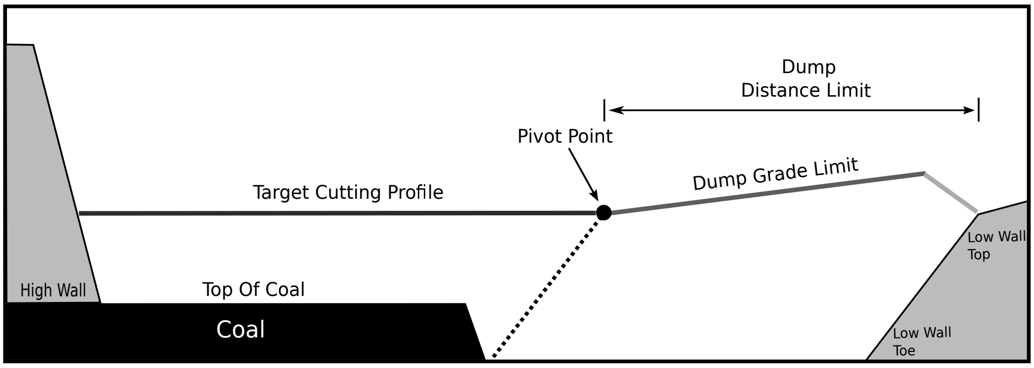
The geometry features are used as a reference to specify the end conditions of each tactic. The geometry features used within the grammar are listed in Table 1.1 and visually depicted in Figure 1.13.

Table 1.1: Geometry Definitions.

Geometry Feature	Definition
TopOfCoal	The interface between the overburden and coal seam.
TargetCuttingProfile	The desired geometry of the overburden after the completion of the bulldozer operation.
PivotPoint	Intersection of 45° line running from the bottom of the coal seam to the target cutting profile.
LowWallToe	The bottom corner of the low wall at the intersection with the void floor.
LowWallTop	The intersection of a plane co-planar with the target cutting profile and the low wall. This is typically close to the inflection point from 45°.
DumpDistanceLimit	Material should be dumped no further than this distance from the pivot point, and is typically the distance from the pivot point to the the top of the low wall.
DumpGradeLimit	Material should be dumped no higher than 20 % uphill from the pivot point.



(a) Geometry definitions applied in a shallow mining operation.



(b) Geometry definitions applied in a deep mining operation.

Figure 1.13: Geometry of pivot push for two example scenarios.

Preparation

The preparation tactics occur directly after blasting of the overburden. Preparation tactics clear steep sections of the overburden and create a traversable grade upon which productive work may begin. Preparation tactics are described in Table 1.2.

Table 1.2: Preparation tactics.

Tactic Name	Definition
EstablishWorkingGrade	Remove the material forming a steep crest at the front face of the blasted overburden, creating a traversible working grade which intersects the pivot point.

Prime Production

Cutting tactics remove material from the overburden region until the design geometry condition is met. Cutting tactics are described in Table 1.3.

Table 1.3: Cutting tactics.

Tactic Name	Definition
ProgressiveGradeCutting	Remove all overburden material above the target geometry by gradually transitioning the grade of the slot floor to horizontal.
ConstantGradeCutting	Remove all overburden material above the target geometry while maintaining the grade of the slot floor but carrying horizontally along the design level.

Dumping tactics add material within a specific region until the design geometry condition is met. Dumping tactics are described in Table 1.4.

Table 1.4: Dumping tactics.

Tactic Name	Definition
TipHeadDownhill	Tip head to advance a dump profile at a downhill grade generally extending from the PivotPoint to the LowWallToe.
TipHeadLevel	Tip head to advance a dump profile at a level grade from the PivotPoint along the plane of the TargetCuttingProfile.
TipHeadUphill	Tip head to advance a dump profile at an uphill grade from the PivotPoint within the DumpDistanceLimit and the DumpGradeLimit.
BackStackDownhill	Back stack to place material into the void until filled level with the plane of the TargetCuttingProfile.
BackStackUphill	Back stack to place material above the filled void within the DumpDistanceLimit and the DumpGradeLimit.

Cleanup

Table 1.5: Cleanup tactics.

Tactic Name	Definition
ClearTopOfCoal	Use bulldozers to carefully remove all remaining material above the TopOfCoal.

Grammar

High-Level description

The following snippet describes the high-level workflow of pivot push.

```
PivotPush = Preparation, "then", PrimeProduction,
[ "then", CleanUp ] ;
```

Preparation

Preparation consists of establishing a working grade which intersects with the Pivot Point.

```
Preparation = "EstablishWorkingGrade", "until", "PivotPoint" ;
```

Prime Production

Prime production is expressed as a cutting description with one or more simultaneous dumping tactics.

```
PrimeProduction = CutDescription , "with",
{ DumpDescription, [ ";" ] } ;
```

Cutting Tactics

The cutting description conveys the tactic which is used to remove material from the overburden region until a goal condition is met.

```
CutDescription = CutTactic, "until", "TargetCuttingProfile" ;

CutTactic = "ProgressiveGradeCutting" | "ConstantGradeCutting" ;
```

Dumping Tactics

Each dumping tactic may continue until either the dump profile intersects with a geometry feature, or when a specified dump distance or dump grade is reached.

```
DumpDescription = TipHeadDownhill | TipHeadLevel | TipHeadUphill |
BackStackDownhill | BackStackUphill ;

TipHeadDownhill = "TipHeadDownhill",
[ "at", NegativeGrade ],
( "until", "LowWallToe" | "for", Distance ) ;

TipHeadLevel = "TipHeadLevel",
( "until", "LowWallTop" | "for", Distance ) ;

TipHeadUphill = "TipHeadUphill",
[ "at", PositiveGrade ],
( "until", "DumpDistanceLimit" | "for", Distance ) ;

BackStackDownhill = "BackStackDownhill",
( "until", "LowWallTop" | "until", Grade ) ;
```

```
BackStackUphill = "BackStackUphill",
( "until", "DumpGradeLimit" | "until", Grade ) ;

Distance = Number , "metres" ;

PositiveGrade = Number , "percent" ;

NegativeGrade = "-", Number , "percent" ;
```

Cleanup

ClearTopOfCoal is required only if the geometry of the strip is such that bulldozers may remove all material down to the coal seam. No specific cleanup operation is required if material remains to be removed by an excavator after the bulldozers have finished their task.

```
CleanUp = "ClearTopOfCoal" ;
```

Example of application of the grammar

Figure 1.14 illustrates a pivot push operation consistent with the following description which obey this grammar.

EstablishWorkingGrade until PivotPoint
then ProgressiveGradeCutting until TargetCuttingProfile
with TipHeadDownhill until LowWallToe ;
BackStackDownhill until LowWallTop ;
BackStackUphill until DumpGradeLimit
then ClearTopOfCoal

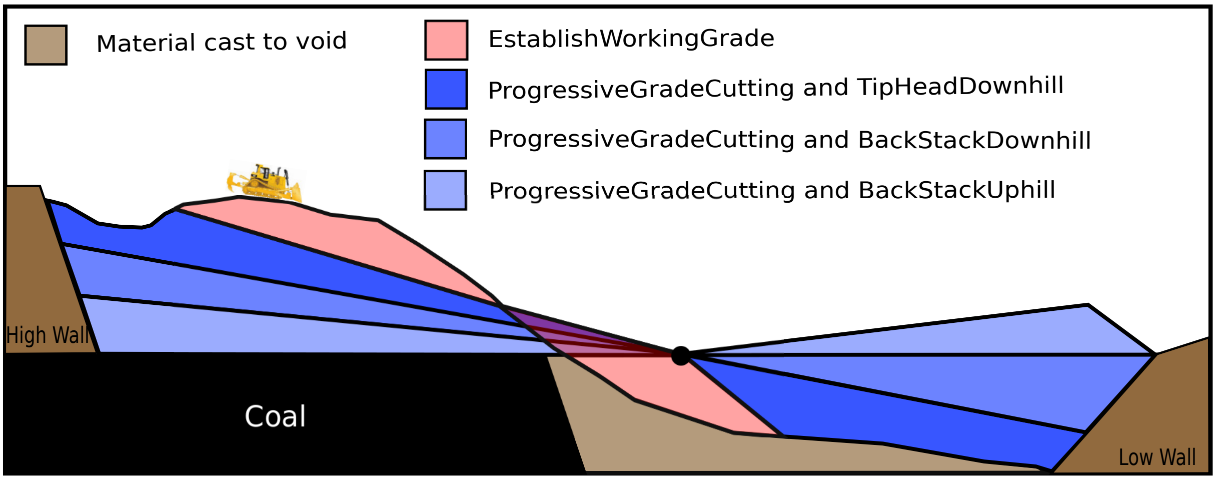


Figure 1.14: An example pivot push method.

Semi-autonomous pivot push bulldozing

This section provides background and rationale for automation and describes the Caterpillar semi-autonomous tractor system, also known as SATS.

The rationale for automation

Autonomous bulldozing has potential to reduce injury, improve reliability, increase productivity and reduce cost.

Operating a bulldozer is one of the roughest operator experiences on a mine site. In the five years leading to 2009, bulldozer-related injuries constituted approximately 21% of all machine-related injuries in Australian surface coal mining [Cooke et al., 2012]. The machines are driven at maximum power over rocky and uneven terrain. This environment subjects the operator to whole-body vibration, a mechanical oscillation of the entire human body which has been linked to long term health issues including damage to the spinal system and sciatic pain [Pope et al., 2002; Miyashita et al., 1992].

Bulldozer operation is monotonous, composed of regularly repeating activities which are executed for up to 12 hour shifts. The sequences of cuts and dumps required to move material can be described using rules that are amenable to automation and while the automation of these machines for pivot push bulldozing is technically challenging, it is also technically tractable.

Pivot push achieves its economies with a highly structured operation style and judicious use of gravity. Execution of the method requires specialized training beyond that required of a bulldozer operator performing standard earthworks. Notwithstanding the training and experience of operators who complete pivot push, they are still challenged to complete the work to specification. Deviations from the plan can cause downstream loss of production, particularly if the variations lead to unnecessary re-handling of material.

The introduction of autonomous haul trucks by Caterpillar [2013] and Komatsu [2014] has been associated with increased utilization and reduced variance, leading to greater productivity for each machine [Parreira, 2013; Brundrett, 2014]. It is conjectured that a bulldozer automation system can also bring higher levels of consistency (reduced variance) to operation leading to productivity improvements.

Labour is one of the significant costs associated with mining [Deloitte, 2016] and autonomous machines offer possibilities for reducing labour costs. In a semi-autonomous pivot push operation it is conceivable that one operator might assume responsibly or oversight for several machines with consequential savings in labour.

These considerations motivate the development of autonomous bulldozers to execute pivot push operations.

The Caterpillar Semi-Autonomous Tractor System

Caterpillar SATS is a semi-autonomous tractor system for D11T bulldozers that can perform bulk earthmoving. At the commencement of the project under which this thesis has been conducted, this technology had been deployed at a Wyoming coal mine where it had moved over 10 million cubic meters of material. At this time, SATS was capable of executing push-to-an-edge bulldozing and was being successfully used for dragline bench preparation [Dyer and Hill, 2011]. The broad aim of the project is to extend the capability of SATS so that the system can perform pivot push bulldozing.

Figure 1.15 depicts the SATS system which comprises three components: (i) an operator station used to generate work plans for the bulldozer and from which the operator provides supervisory control of the machine; (ii) a D11T bulldozer equipped with sensing and on-board computing capabilities to support semi-autonomous operation; and (iii) a 2.4 GHz communication link between the operator station and the bulldozer over which telemetry data is provided to the operator and mission plans are provided to the bulldozer. The telemetry data from the bulldozer includes visual information provided by CCD cameras, localization information provided by a navigation system, and various indicators of machine state such as engine speed and fuel rate. The system is designed such that up to five machines can be simultaneously supervised from one operator station.

SATS automates slot bulldozing. At any time each machine works within one slot of the strip. There are typically between 20 to 50 slots. The workflow is as follows. The operator first chooses a slot

(a) The operator station.

(b) The Caterpillar D11T bulldozer.

Figure 1.15: The operator station and D11T Components of the SATS system. A wireless data link enables the transmission of information between the bulldozer and the operator station.

to operate in. They then identify the material to be removed from the slot using a Tactical Planner interface. The automation system then plans and executes the moves, cuts, carries, and dumps needed to effect the identified material movement.

The Tactical Planner interface includes a top-down view of the work area, showing the locations of each slot in the push, and a cross-section view, showing the geometry of the slot in which the bulldozer is currently located. The locations of the slot boundaries are specified in a planning phase and do not change throughout the operation.

A machine is capable of continuing without operator intervention for up to 15 minutes, this time being specified through a risk identification process. The operator takes on a largely supervisory role, with their major task being to reposition the bulldozer to the next slot under teleoperaton. Their other work involves ensuring that all machines have sufficient work assigned so as not to sit idle.

The bulldozer is commanded by the operator under remote control when transitioning between and establishing slots, clearing uneven terrain, relocating between slots or travelling into and out of the work area. The operator's control interface includes directional and steering controls, blade positioning control and foot brakes. The operator determines their understanding of the machine's environment through camera displays, plan view and cross sectional views of the machine within the work area and the replay of audio which is recorded on-board the machine.

The elements of perception provided to the operator are consistent with recommendations from Dudley [2014] who found that camera vision and a goal-orientated task visualization were of primary importance over motion and audio feedback when assessed by their impact on the production rate of a bulldozer under remote operation. Even so, it remains a challenge for the operator to properly gauge the level to which the blade is filled from their limited vision through the camera feeds. Remote operation is therefore less productive than autonomous operation and it is best to return command to the autonomous system whenever possible.

SATS makes use of several existing blade control systems already included on the Caterpillar D11T. AutoBladeAssist (ABA) provides automatic switching between preset positions and AutoCarry takes command of the blade control during the carry portion of a bulldozing cycle.

ABA is a blade pitch control system which moves the blade into preset positions typically required in a slot bulldozing cycle [Caterpillar, 2016]. Cutting generally requires the blade pitched forward to aggressively dig into the material. Carrying requires the blade pitched back so that no more material enters the blade. Dumping requires the blade to pitch forward so that all material leaves the blade. SATS blade pitch control is handled by toggling between these preset locations at the appropriate point within the cycle.

AutoCarry is a blade load control system which automatically maintains an optimally-sized blade load [Caterpillar, 2016]. The ideal blade load is maintained by lowering or raising the blade to adjust the volume of material carried within. The properties of bulldozer traction are such that ideal productivity is achieved when pushing a blade load large enough to cause 5-10% track slippage depending on machine grade and material properties. A lower track slip value indicates that the blade load is too small while a higher track slip value would indicate the travelling velocity is too low. Blade volume cannot be measured directly, so AutoCarry uses a tractive model to determine this ideal track slip value, and controls blade load through the proxy of track slip. AutoCarry is generally able to maintain a greater blade load than manual operators, resulting in an increased overall production rate when used as an operator assist feature on otherwise manually-operated machines.

Thesis overview

The three chapters that follow each directly address a thesis aim.

Chapter 2 addresses Aim 1 of the thesis and validates a simulation framework for pivot push productivity.

Chapter 3 addresses Aim 2 of the thesis and uses the validated simulation framework to explore how best to execute pivot push bulldozing.

Chapter 4 addresses Aim 3 of the thesis and evaluates the performance of a semi-automated bulldozer performing the pivot push method identified by Aim 2.

Chapter 5 summarizes the thesis and makes recommendations on future work.

CHAPTER 2

Validating predictions of productivity for a pivot push operation

Predicting progress.
of pivot push bulldozing
is a sine qua non

Introduction

This chapter addresses the first thesis aim: *validate a simulation framework for predicting the productivity of pivot push.* The pivot push simulation framework is described in Hensel et al. [2017] and has been developed within the broader work of this project. The simulation framewowork is a collection of C++ applications which run simultaneously and exchange information to facilitate the simulation of the operation and recording of productivity [1]. An overview of the architecture is shown in Fig. 2.1. It consists of four main interacting components:

1. A Terrain Simulator that maintains a model of the strip workspace and simulates the effect of bulldozer motions on the terrain. This includes: (i) a discretized height-grid representation of the terrain; (ii) a model that describes how material is pushed when a bulldozer blade enters a cell of the height-grid; (iii) a model, developed by Bettens [2016], that describes the interaction between the bulldozer and its terrain to determine the pushable blade load based on travelling grade; and (iv) a model of how pushed material flows under the influence of gravity.

[1] The software components themselves are subject to confidentiality considerations and are therefore not released publicly here. For more information , interested individuals may contact the principal investigator of the larger project and supervisor of this thisis, Ross McAree (p.mcaree@uq.edu.au)

2. A Tactical Planner which plans and executes the sequence of cuts and pushes to achieve the target terrain following a specified pivot push method. This includes: (i) a strip manager to track high-level slot information and to determine the slot and strategy the bulldozer should use for its next sequence of pushes and (ii) a set of pivot push methods consistent with the grammar of Chapter 1 that consider the current workspace terrain and determine a method-specific goal, a next milestone towards the goal, and a next cut towards the milestone.

3. A Production Monitor that tracks bulldozer activities and the movement of material to facilitate the calculation of productivity along with other representative metrics such as volume moved and distance travelled per cycle.

4. A Dozer Visualizer that allows the progress of the push to be monitored, see Fig. 2.2.

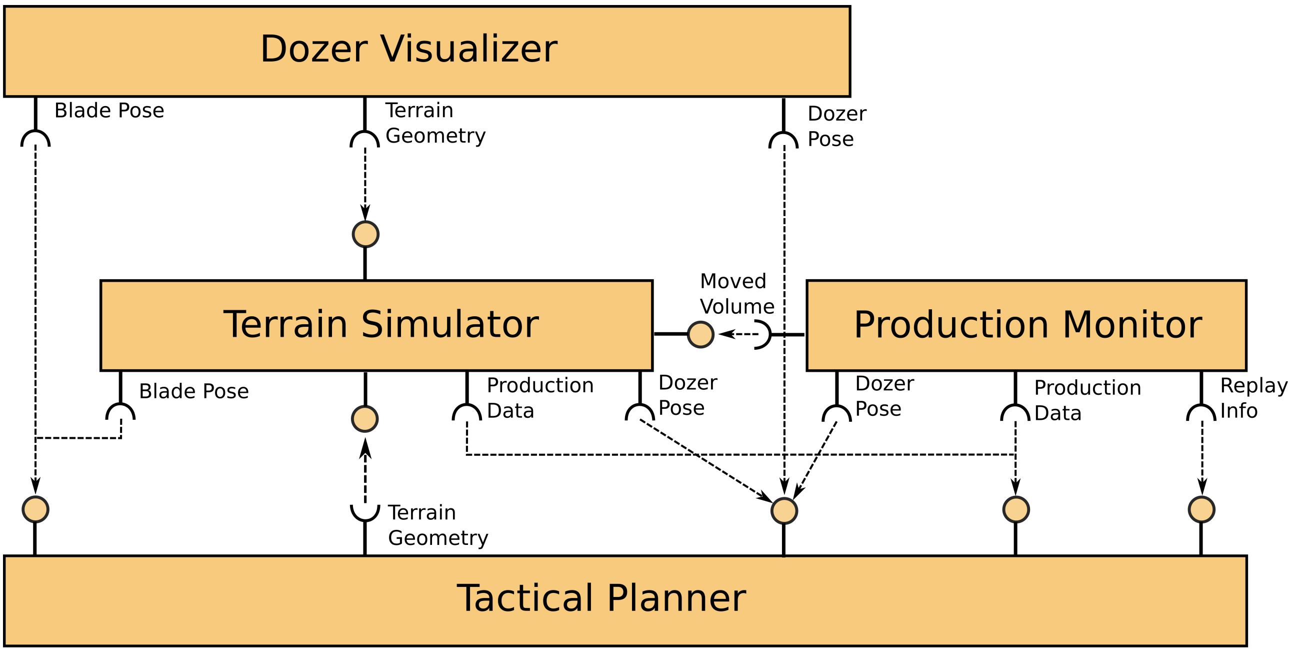


Figure 2.1: A component diagram showing the architecture of the pivot push simulation framework.

The simulation framework allows the movement of material to the void to be simulated push-by-push according to a specified pivot push method and gives estimates of productivity.

The ultimate purpose of the pivot push simulation framework in this thesis is to predict productivity of a bulldozer subject to the geometry of the strip and pivot push method. Productivity is most easily visualized as a *production curve*, generated by plotting the cumulative sum of material volume moved to prime on the y-ordinate and the cumulative sum of time spent in effective work on the x-ordinate. From such a chart, the instantaneous productivity at any time in the operation can be computed as the gradient of the line.

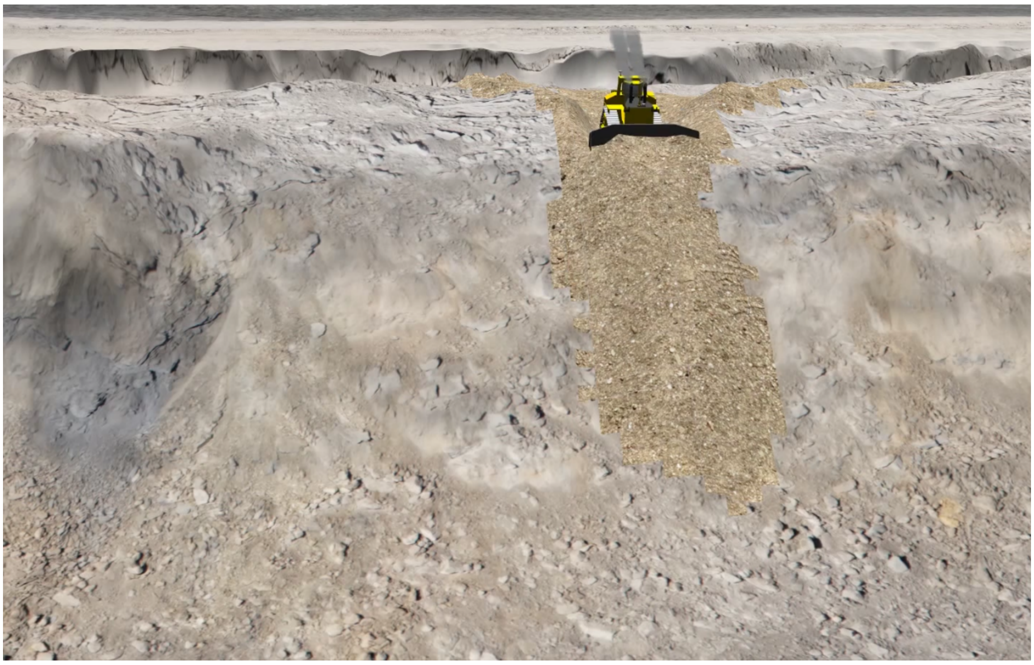


Figure 2.2: The Dozer Visualizer is used to monitor the progress of a bulldozer in simulated pivot push. The effect of the Terrain Simulator is seen as material is caused to flow down the front of the overburden face in response to the actions of the bulldozer blade.

The methodology used in this chapter is to compare the operation measured during the validation trial against what was generated by the simulation framework. The validation consists of two components: (i) a *macro*-scale validation which determines if the simulation framework is capable of generating a production curve which is aligned with measurements from aerial survey (the subject of Section 2.5); and (ii) a *micro*-scale validation which examines characteristics of the individual bulldozer actions such as velocity of travel and volume moved per cycle (the subject of Section 2.6).

The motivation for undertaking a validation of the simulation framework is to establish confidence in the predictions it makes so that (i) they can be used to compare the performance of different pivot push methods (the topic of Chapter 3) and (ii) to provide a reference against which the productivity of an autonomous pivot push can be measured (the topic of Chapter 4). Three different pivot push methods are directly validated.

Pivot push productivity

Productivity is broadly defined as the effectiveness of productive effort, as measured in terms of the rate of output per unit of input [Parker, 2003]. This thesis defines pivot push productivity to be the volume of material moved to prime per hour.

The measurement of time requires some discussion. Four measures of time are of interest in considering productivity.

1. **Calendar time.** This represents the maximum time that is available for productive work and productivity per hour of calendar time is critical to a mining enterprise.

2. **Available time.** This represents the time in which the machine is available to be used for productive work. This excludes down time, when operation is not possible because of planned maintenance or breakdown [Lukacs, 1998].

3. **Utilized time.** This is the time spent while an operator is actively using the machine. This excludes delay time which arises for example due to process inefficiencies and human factors [Lukacs, 1998].

4. **Effective time.** This is the component of utilized time the machine spends undertaking productive pivot push effort within a strip. This excludes time spent undertaking other activities such as road maintenance, transit between work areas or idling.

The validation of this chapter is based on comparisons of volume moved to prime per unit of effective time.

The three push methods used for validation

The three pivot push methods selected for validation are described below. These three methods were chosen after consultation with industry experts [Medland, 2015; Nott, 2015] based on their understanding of the most productive push methods. The pivot-push grammar of Chapter 1 is used to describe each method and each is also illustrated diagrammatically.

Method 1

EstablishWorkingGrade until PivotPoint
and ProgressiveGradeCutting until TargetCuttingProfile
with TipHeadDownhill until LowWallToe ;
BackStackDownhill until LowWallTop ;
BackStackUphill until DumpGradeLimit.

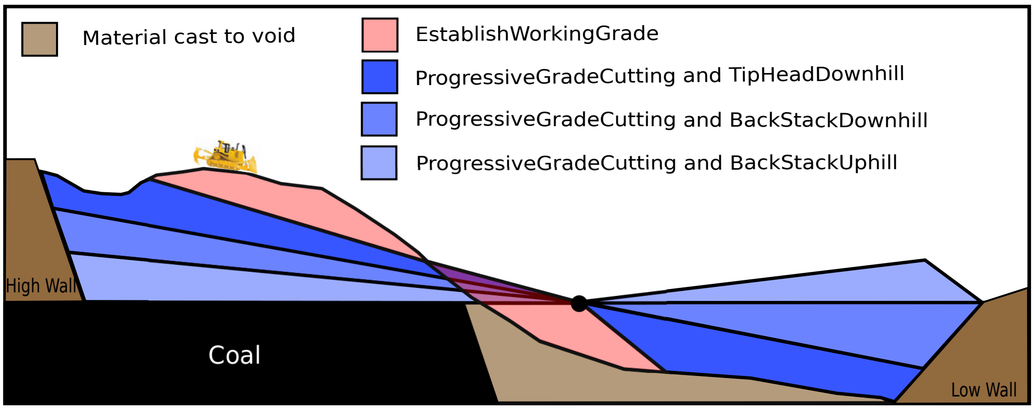


Figure 2.3: A graphical cross-section depiction of Method 1.

Method 2

EstablishWorkingGrade until PivotPoint
then ConstantGradeCutting until TargetCuttingProfile
with TipHeadLevel until LowWallTop ;
TipHeadUphill until DumpDistanceLimit.

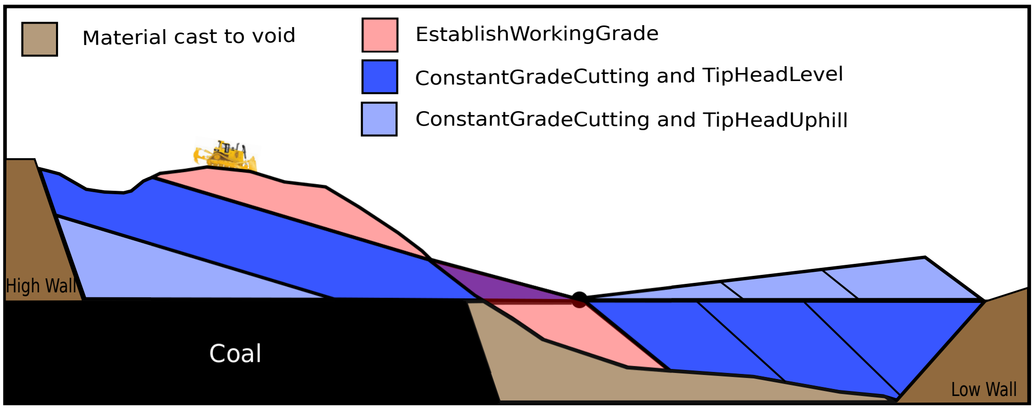


Figure 2.4: A graphical cross-section depiction of Method 2.

Method 3

EstablishWorkingGrade until PivotPoint
then ConstantGradeCutting until TargetCuttingProfile
with TipHeadLevel until LowWallTop
then BackStackUphill until DumpGradeLimit.

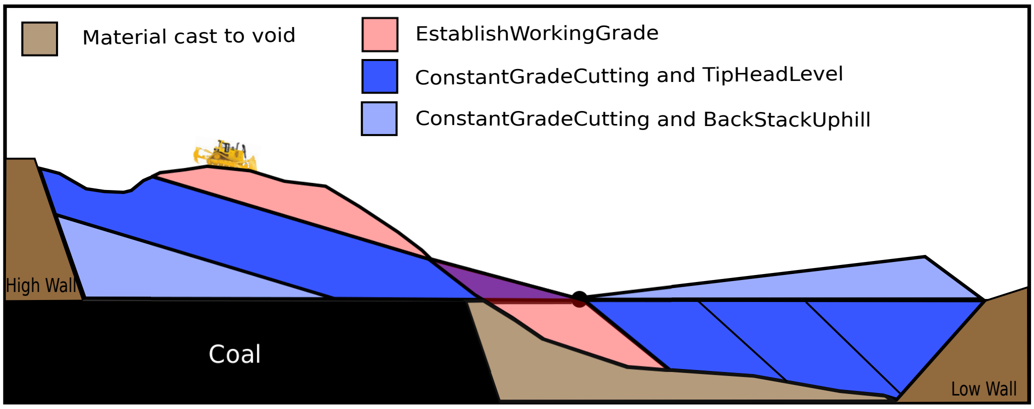


Figure 2.5: A graphical cross-section depiction of Method 3.

Validation trial

The trial conducted to validate the predictions of the simulation framework (the validation trial) took place at Wilpinjong colliery from 10 October until 24 December 2015. The trial monitored a single manually-operated bulldozer (Bulldozer 2010) as it worked under three different pivot push methods. A production strip with layout as shown in Figs. 2.6 and 2.7 was dedicated to the study. The strip had dimensions of 250 m long by 130 m deep and was divided into three regions each approximately 60 m long. Method 1 was implemented in the first region, Method 2 in the second region and Method 3 in the third. Of interest to the experiment was the 20 m zone (see figures) at the centre of each of the regions. It was only within these zones that the productivity was measured. The three zones were to be worked only by Bulldozer 2010. The edges of each region were used as a buffer so that any elevation difference between zones could be gradually transitioned.

Bulldozer 2010 was instrumented to enable its activities to be monitored. Instrumentation included a RTK-GNSS aided [Langley, 1998] navigation system that was able to track the bulldozer's position and orientation, displacement transducers to measure the positions of the blade lift cylinders, and a data logging system to record these signals along with a suite of measurements provided by the bulldozer control system. Bulldozer 2010 is shown in Fig. 2.8. A list of recorded data channels and their sample rates is given in Appendix C.

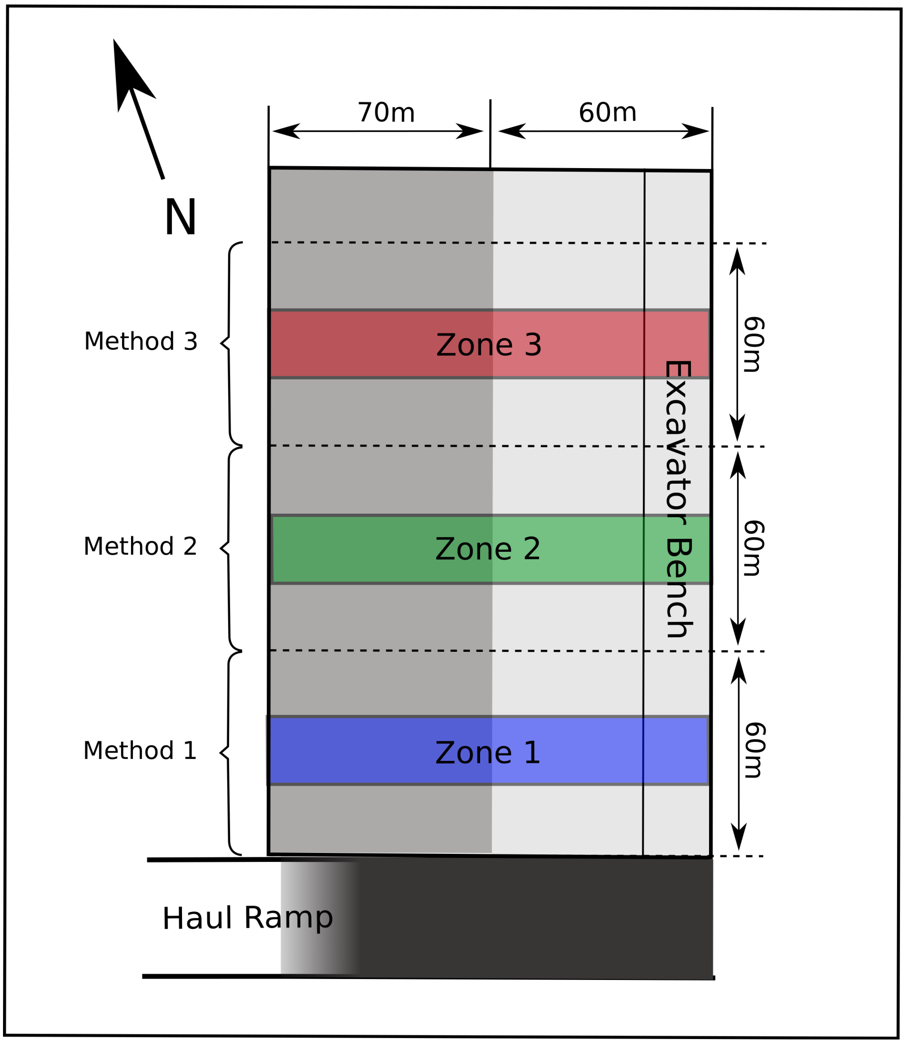


Figure 2.6: Layout of experimental zones within the strip.

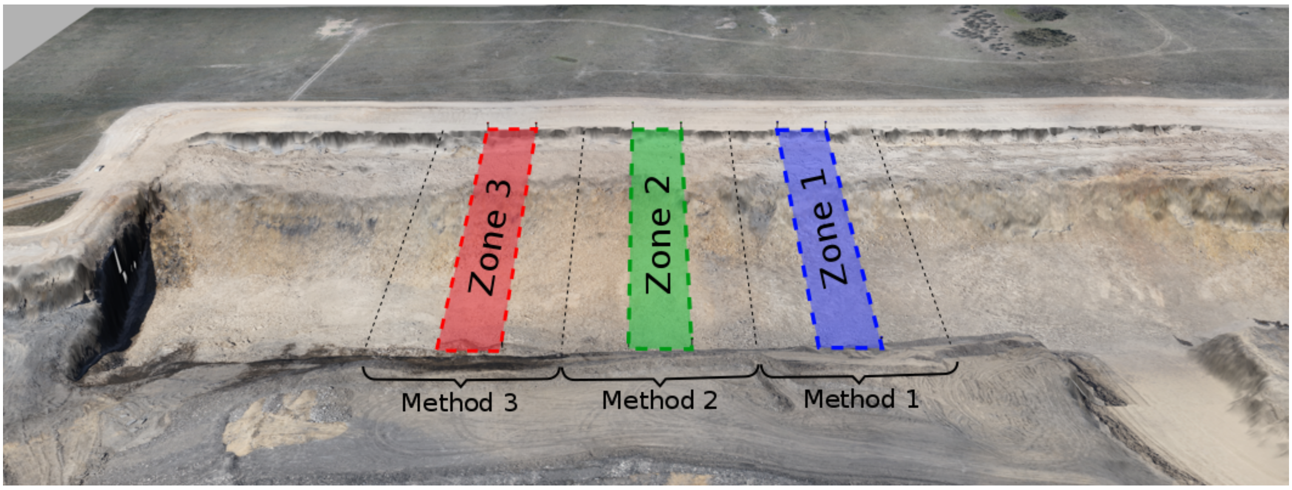


Figure 2.7: Location of experimental zones shown on a 3D rendering of the trial strip in the post-blast state.

Figure 2.8: Bulldozer 2010, the instrumented bulldozer used as the focus of the validation trial.

To ensure deadlines for strip completion were met, other bulldozers were from time-to-time present in the strip. The operators of other bulldozers were instructed to work only in the regions between and outside of the zones. The work done by other bulldozers within the strip was not captured as these machines were not equipped with the same sensors and logging capability as Bulldozer 2010.

All bulldozer operators who worked in the strip were instructed to employ the pivot push method relevant to the area in which they were located, e.g. when in Zone 1 they were to execute Method 1. Operators received information on their location from a Leica JDozer fleet management system [Leica-Geosystems, 2013] installed on each bulldozer. This fleet management system shows the operator the strip design indicating where the bulldozer should cut and where it should fill. The bounds of the experimental zones within the strip were displayed graphically in plan view through the JDozer system, and marked with physical indicators placed at the low wall in the operator's forward view. The site Dozer Push Supervisor provided on-going guidance to the operators on the progress of each of the three zones and had responsibility for ensuring that the specified method was followed in each zone. Eight operators worked in Bulldozer 2010 through the period of the validation trial. The operators worked rotating shifts of five-days at work followed by five days off work.

The volume moved within each zone was measured by aerial survey, following the methodology of

Appendix B. Nine aerial surveys were obtained over the duration of the trial, with the timing of each survey constrained by the availability of the UAV used to capture aerial photographs of the strip area. This resulted in irregular periods between surveys. These surveys are referred to below by the names Survey 1 to Survey 9. A survey taken after the overburden blast but prior to the commencement of the trial is called Survey 0. Timing of the surveys is indicated in Fig. 2.9.

The hours spent in effective effort were obtained by monitoring bulldozer activity using recorded data logs. Effective time was measured by accumulating time the bulldozer spent in motion while located in each zone, including time spent in transit between slots, but excluding time the bulldozer was idle. Bulldozer location was established from the navigation system.

The pivot push simulation framework was used to predict the production-verses-effective time characteristic (the production curve) for each of the three zones in the strip. The simulation followed the specified pivot push method for each zone. The starting terrain was taken from a survey of the post-blast profile obtained before the experimental trial commenced (Survey 0). The target cutting profile was obtained from the pivot push design generated by the mine technical services office. The simulation ran in each zone from Survey 0 until the target cutting profile was reached.

Components of the simulation framework were also used to augment the dataset recorded on Bulldozer 2010. Recorded data was replayed through the Terrain Simulator, which maintained a progressively-updating terrain map and estimated the per-cycle volume moved to prime. Data was also fed into the Production Monitor which provided representative metrics of the operation used in post-analysis.

Issues encountered in the collection of data

Several issues were encountered in the collection of the validation dataset that impacted on the determination of effective time spent in the zones. These included:

- GNSS and network failures. At several points in the trial, the RTK-GNSS system used to determine the position of the bulldozer failed to produce accurate results. These outages were due to loss of RTK corrections due to temporary failure of the network over which they were broadcast and/or failure of the GNSS system to find an accurate solution due to reduced view of the sky. The effect of these failures was that the precision of the GNSS fix degraded from RTK precision (less than 10cm) to standard GPS precision (approximately 1-2 m). The bulldozer's location information is primarily used to indicate in which zone it was currently spending its time. Even with this imprecise fix, each production bulldoing slot is wider than double the magnitude of the location uncertainty. Therefore it is unlikely that these events of lost RTK corrections resulted in misidentification of the current slot being worked and the detrimental effect of these instances is realtively low.

- Logger system failures resulting in no logged data. Over the period of the trial, the logger system on-board the bulldozer failed to log data on several occasions due to technical issues, meaning the work done during such times was unrecorded. Each of these occurences had a detrimetal effect because alternative methods were required to determine how much time was spent in the slot during these outage periods. These methods are detailed in the following parts of this section.

- Work done by other bulldozers in the zones. The experimental protocol stipulated that only Bulldozer 2010 was to do work in the experimental zones. Nevertheless on several occasions other bulldozers contributed to the push in the zones. In the day-to-day working of pivot push, where the work process was non-standard because of the use of different methods side-by-side, operators became uncertain about where they could and couldn't work. Since these other bulldozers were not instrumented, their effective times in the respective zones was not captured. The effect of these instances was essentially the same as the previous, and the method of estimating the amount of time spent during these occurrences is the same.

- Midway through the trial, the need by the mine site to complete other production work with Bulldozer 2010 resulted in the trial being suspended for a period of three weeks (between Surveys 7 and 8). During this time, some unmonitored work was done by other bulldozers in the trial area.

As a consequence of these issues, some of the effective time between Surveys 7 and 8 was not recorded. The un-logged work done within the zones is termed *unaccounted-for*. While these issues were all foreseen and controls were in place to deal with them, these controls proved ineffective in the complex environment of an operating mine.

Figure 2.9 presents a timeline showing the progression of the operation in each of the three zones. The instrumented bulldozer worked the trial area applying the three pivot push methods in each zone as appropriate and ensured the progression of the push in each was consistent with the rest of the strip. Outages of RTK corrections were seen throughout the duration of the trial, and instances of unaccounted-for work were seen in the period between Surveys 7 and 8. Also shown is the three-week delay in which the trial was suspended.

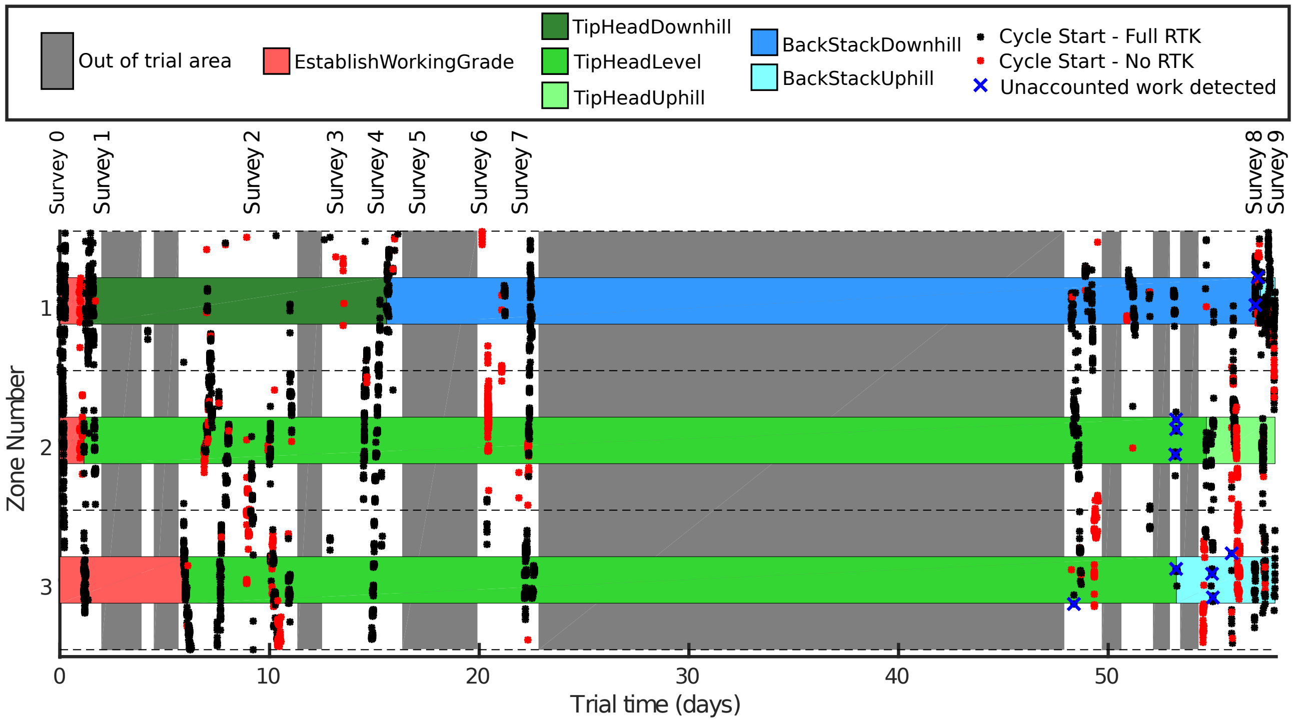


Figure 2.9: A timeline of the validation trial. The three horizontal coloured bars represent the progress of pivot push in the three zones. The colouring of the bars represents the dumping tactic. Circular markers represent the location of Bulldozer 2010 at the beginning of each cycle. The colour of the markers represent the status of the GNSS solution during that cycle. Blue crosses identify unaccounted-for work, which is a result of either a temporary failure of the logging system or work completed by another bulldozer.

Unaccounted-for effective time has been estimated in post analysis of collected data by employing the Terrain Simulator. The Terrain Simulator was used to maintain a progressive terrain map by replaying the logged movements of Bulldozer 2010, including the position and orientation of its blade. Unaccounted-for work was identified when the last known profile of a slot differed from the current terrain profile as shown in Fig. 2.10. The volume difference between the previous and current terrain profile represents unaccounted-for work done. The amount of time spent moving this unaccounted-for volume was determined by assuming a representative rate of material movement consistent with what had been previously observed.

This method of estimating unaccounted-for time is less than ideal, and is subject to significant uncertainty. Uncertainty arises in the estimation of material volume which was moved and in the estimated rate at which this material was moved.

The estimation of unaccounted-for volume moved was made difficult if it coincided with a loss of RTK corrections. This led to a degradation in the reliability of the progressive terrain map from which unaccounted-for volume was estimated.

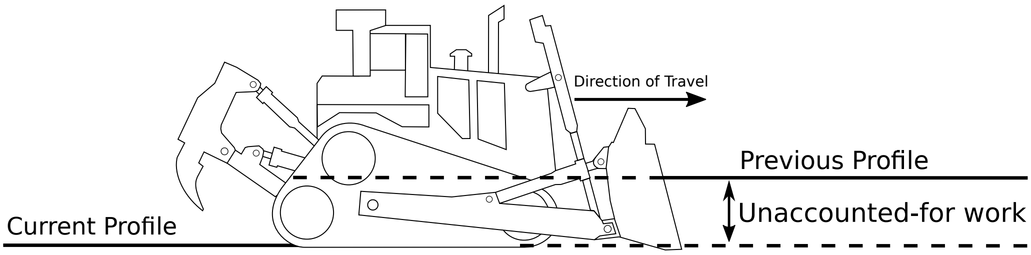


Figure 2.10: Unaccounted-for volume is identified when the current terrain profile differs from the terrain profile mapped during previous passes.

Estimation of production rate is difficult as the rate is not constant throughout the operation. Recall that the productivity of pivot push decreases throughout the operation as the per-cycle distance and grade of travel increases. An attempt was made to estimate the production rate between Surveys 7 and 8 by extrapolating a logarithmic function from the production rate observed in earlier survey measurements. This method is sensitive to noise in the earlier survey measurements and the uncertainty of this extrapolation is assumed to be $\pm$ 10 %.

Table 2.1 summarizes the calculation of time which was spent moving unaccounted-for material.

Table 2.1: Unaccounted-for time estimated for each zone between Surveys 8 and 9

Zone number	**Measured time (h)**	**Unaccounted-for volume (m^3)**	**Assumed production rate (m^3/h)**	**Unaccounted-for time (h)**
1	7.97	672 ± 363	525 ± 52.5	1.28 ± 0.91
2	15.09	3662 ± 836	525 ± 52.5	6.97 ± 2.54
3	12.65	2598 ± 292	525 ± 52.5	4.94 ± 1.16

Swell of material

The Terrain Simulator is able to replicate the effect of material swell/compaction in response to disturbance by the bulldozer. Figures 2.11 and 2.12 show the variation in volume within each zone. These figures suggest there was no significant change in material volume throughout the trial [2]. Accordingly the simulations used in validation are executed with an assumption of fixed material volume.

[2]Note that the total volume measured here is inclusive of all overburden material which is present in the zone. The production curve results in Section 2.5 only includes material which is to be pushed - excluding material which was already cast into the void.

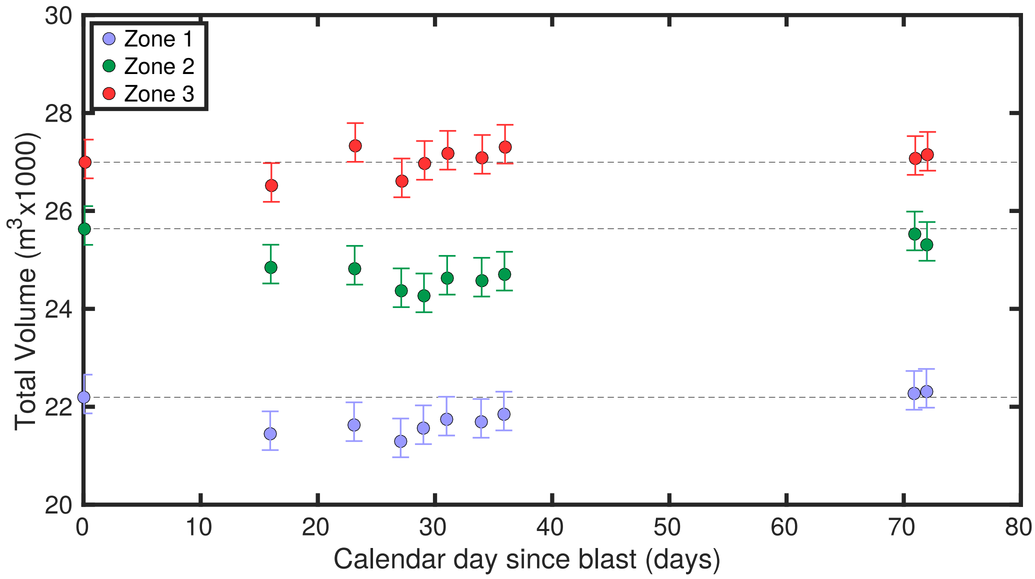


Figure 2.11: Total volume change during the trial. Vertical error bars indicate the range of survey measurement error as determined in Appendix B.

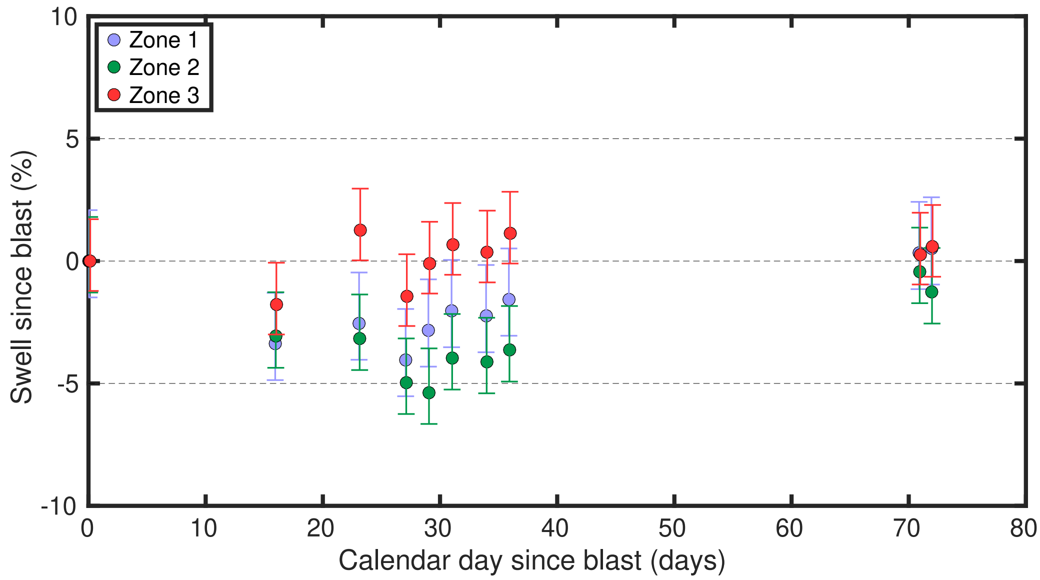


Figure 2.12: Percentage of volume change during the trial.

Cumulative production validation

This section conducts a *macro*-scale validation of the simulation framework by comparing a simulated production curve against the production curve which was measured during the trial.

Simulated times are determined by accumulating the per-cycle time spent in each zone. Simulated volumes are determined by accumulating the per-cycle volume moved into the prime region of each zone. Measured times are determined by accumulating time spent within each zone, and are modified to include the unaccounted-for time identified in Table 2.1. Horizontal error bars signify the uncertainty around the lost time estimation. Measured volumes are determined as the difference in volume from the initial post-blast survey specifically within the prime region. Vertical error bars signify the mean measurement error determined using the methodology presented in Appendix B.

It is found that the measured production as represented by survey points is closely aligned with the production curve obtained from simulation. Some general observations are made:

- Surveys 1-7 are generally closely matched with the simulated reference. Surveys 8 and 9 are also closely matched to simulation, but with increased horizontal uncertainty due to the issues encountered during the trial.
- The simulated and measured production curves all begin with a near-horizontal gradient which steadily increases. This occurs during the operation phase of Establish Working Grade, where material cannot yet be pushed directly to the prime region, resulting in a low productivity.
- The productivity of the bulldozer decreased over the duration of the trial, as seen by the steady reduction of gradient. This is due to increases in travelling distance and travelling grade as the void is filled.

Method 1

The production curve in Figure 2.13 compares measurement against simulation for Method 1.

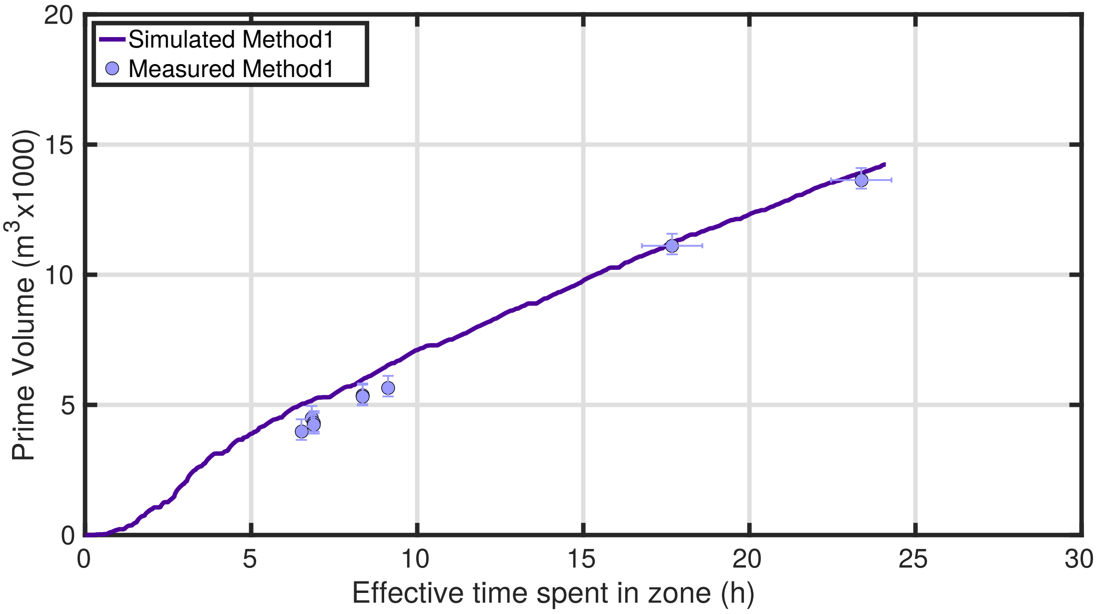


Figure 2.13: Comparison between measured and simulated production in zone 1.

Method 2

The production curve in Figure 2.14 compares measurement against simulation for Method 2.

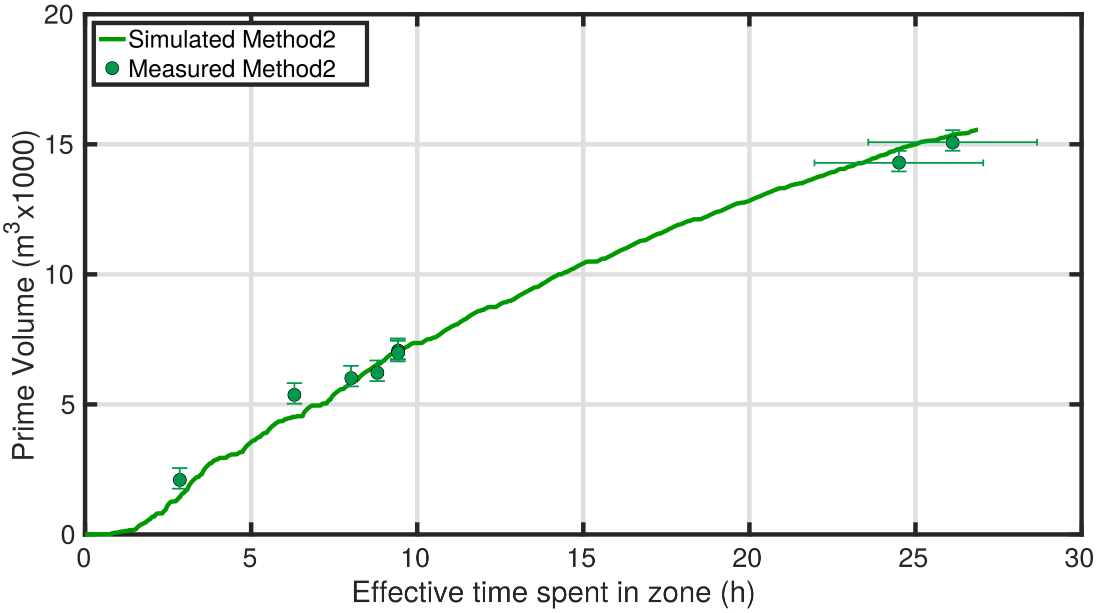


Figure 2.14: Comparison between measured and simulated production in zone 2.

Method 3

The production curve in Figure 2.15 compares measurement against simulation for Method 3.

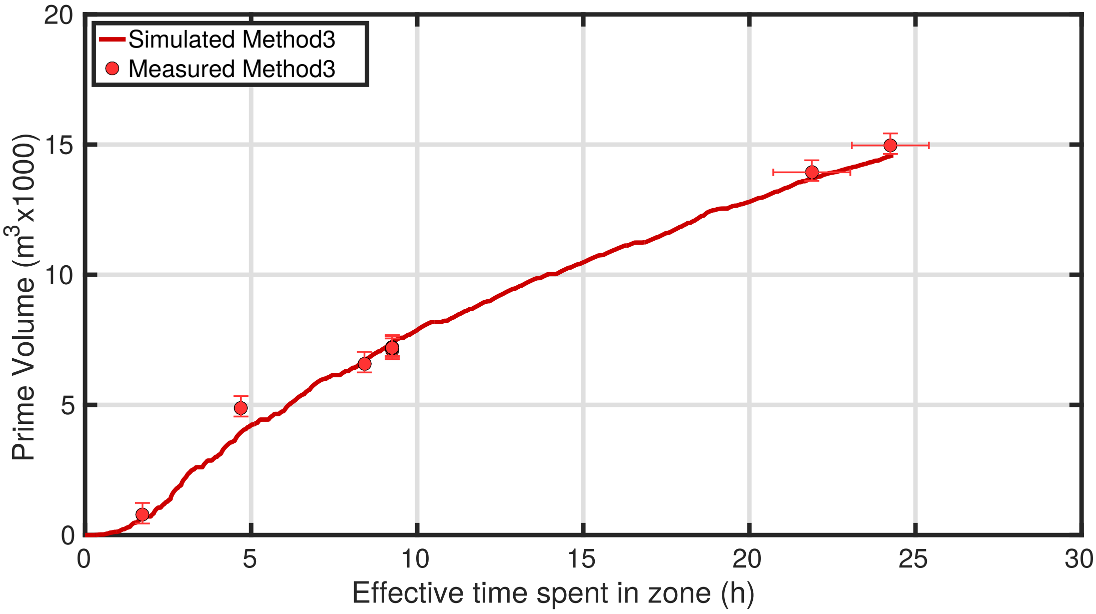


Figure 2.15: Comparison between measured and simulated production in zone 3.

Comparison of simulated pivot push to actual pivot push

The macro-scale validation found the simulation framework able to predict the production curve of manual pivot push for a given strip geometry and pivot push method.

The purpose of this section is to gain understanding of how the simulation compares to measured operations on the *micro*-scale, that is, the characteristics of the individual actions performed by the bulldozer within pivot push. The following aspects are explored: (i) the shape and progression of the terrain; and (ii) the productivity per cycle. Appendix D augments the discussion, presenting a comparison of (i) the progression of cutting and dumping locations; (ii) the velocity of travel; (iii) the volume moved to prime per cycle; and (iv) the simulated grade vs the actual grade of travel.

The shape and progression of the terrain

Figures 2.16, 2.17, and 2.18 compare an intermediate pivot push terrain from aerial survey against that generated by the simulation framework. These snapshots of the terrain were taken when the simulation and survey show a comparable progress to completion but not necessarily when the same amount of time has been spent in the zone.

There are two key differences between the predictions made by the simulation framework and the measurements obtained through aerial survey: (i) the frequency of highwall bench clearing, that is the moving of material in the strip by an excavator at the highwall; and (ii) the steepness of the grade away from the highwall bench. These two differences are closely related.

The width of the highwall bench must be at least the length of the bulldozer (12 m) but can be larger depending on the size of the excavator. For the validation trial, a 20 m wide bench was used. In simulation the highwall bench is cleared when no more work can be done by the bulldozer in strict adherence to the maximum grade constraint of -25 % as presented in Appendix A. In practice the bench was cleared when the highwall excavator was available. Manual operators nonetheless continued removing material from the overburden region while the excavator bench remained unchanged. This led to the development of a significantly steeper grade adjacent to the excavator bench and in practice grades up to -40 % were observed.

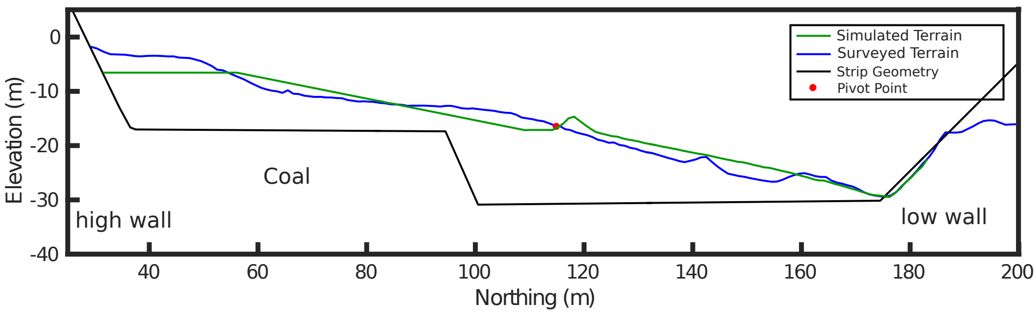


Figure 2.16: Representative cross sections of Zone 1. This cross section shows the terrain just after the completion of the TipHeadDownhill dumping tactic.

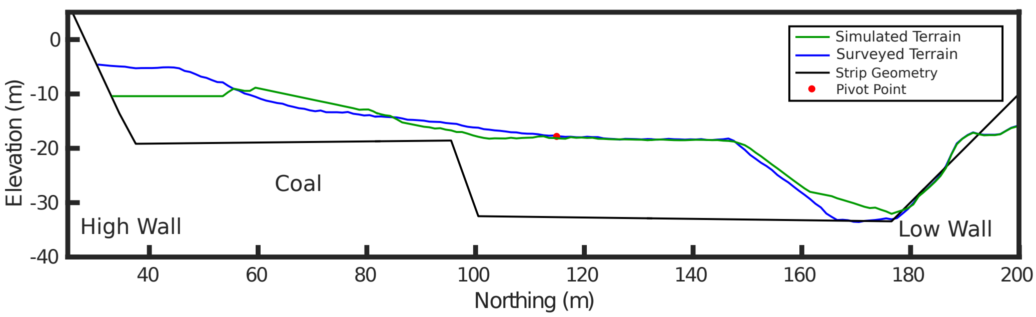


Figure 2.17: Representative cross sections of the cutting method in Zone 2. This cross section shows the terrain mid way through the TipHeadLevel dumping tactic.

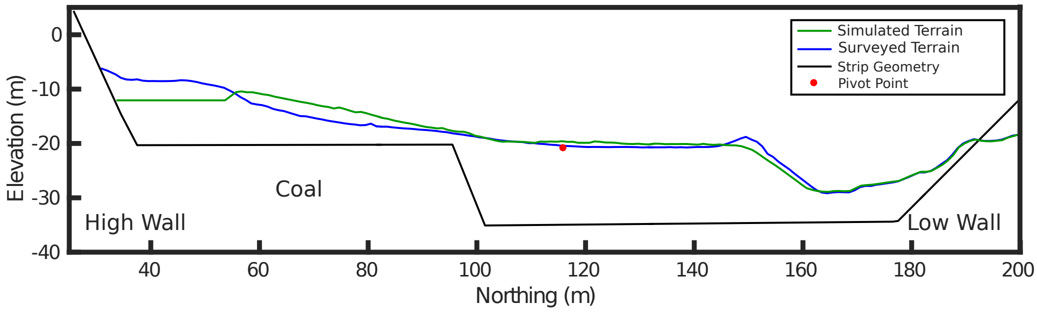


Figure 2.18: Representative cross sections of Zone 3. This cross section shows the terrain midway through the TipHeadLevel dumping tactic. The pile is left at the tip head as a safety control to prevent the bulldozer from going over the tip head, see Appendix B. The simulation, by contrast, does not leave a pile.

Productivity per cycle

Aerial survey provides an accurate and complete map of the terrain to be used for productivity calculation, however it is only able to deliver a measurement once in several hours of operation.

To obtain an estimate of productivity on a per-cycle basis, data recorded during the validation trial was played through components of the simulation framework. Specifically the position and orientation of the bulldozer body and the bulldozer blade were replayed to simulate the movement the bulldozer and its effect on the material.

Productivity of a cycle is defined as the volume moved to prime divided by the effective time during one slot bulldozing cycle. Replaying measurement through the Terrain Simulator provides an estimate of per-cycle volume moved by the bulldozer (called *calculated-from-measurement* productivity). Figures 2.19 to 2.24 compare the calculated-from-measurement productivity against that predicted through simulation. The height of each bar in the histogram is the sum of effective time spent within cycles of a specific productivity. The mean productivity shown in each chart represents the mean production rate weighted by effective time in cycle.

Several points are worth noting:

- The area of the calculated-from-measurement productivity histograms is lower than those of the simulations because of unrecorded effective time issues, see Section 2.4.1.
- Figures 2.19 to 2.20 for Zone 1 and 2.23 to 2.24 for Zone 3 have similar productivity ranges and distributions. The histograms for Zone 2 (Figures 2.21 to 2.22) are not similar. The manual productivity per cycle in zone two does not conform to the same gaussian-like distribution. It is difficult to determine if this difference was due to some aspect distinct to the method or if it was due to other operator behaviours in this zone.

- The mean computed-by-measurement productivity (see Table 2.2) is slightly higher (by 2.8% to 6.1%) than the simulated productivity.

Method 1

Figures 2.19 and 2.20 compare the productivity while completing Method 1.

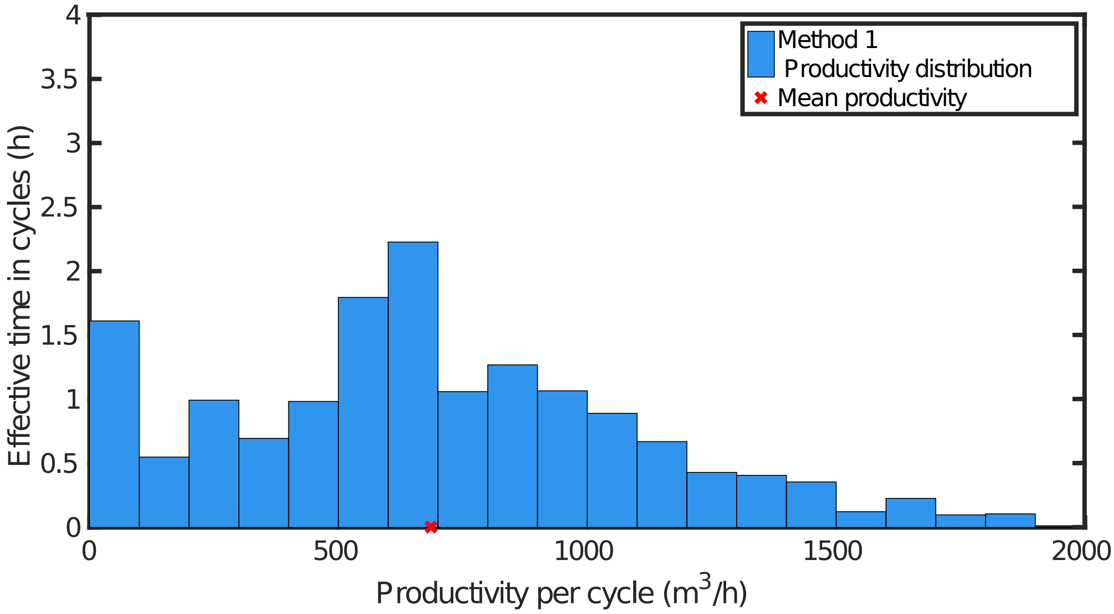


Figure 2.19: Computed-from-measurement per-cycle productivity in Zone 1.

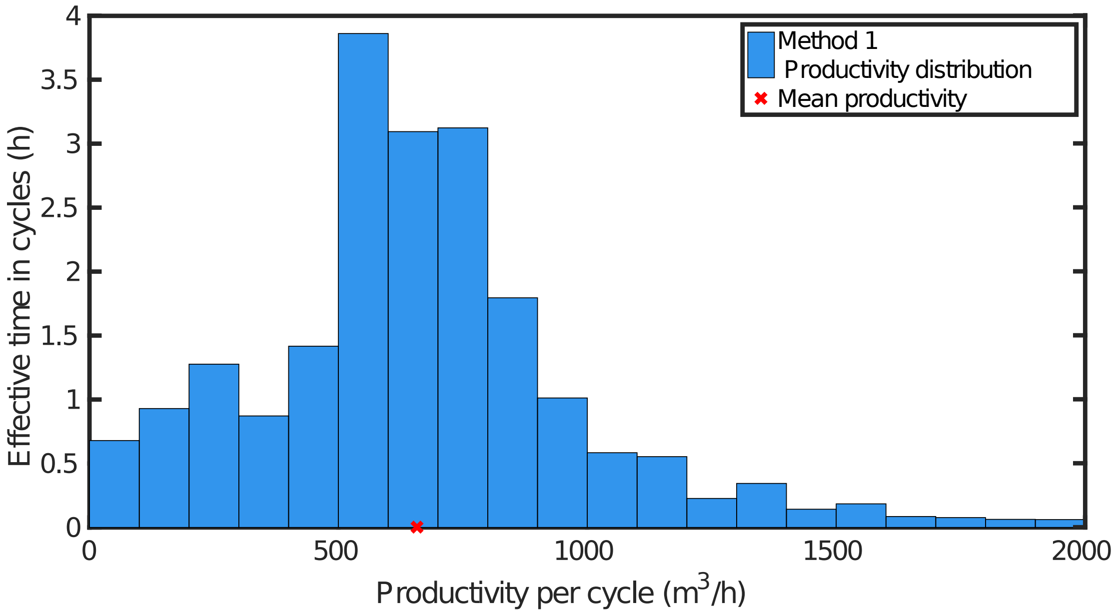


Figure 2.20: Simulated per-cycle productivity in Zone 1.

Method 2

Figures 2.21 and 2.22 compare the productivity while completing Method 2.

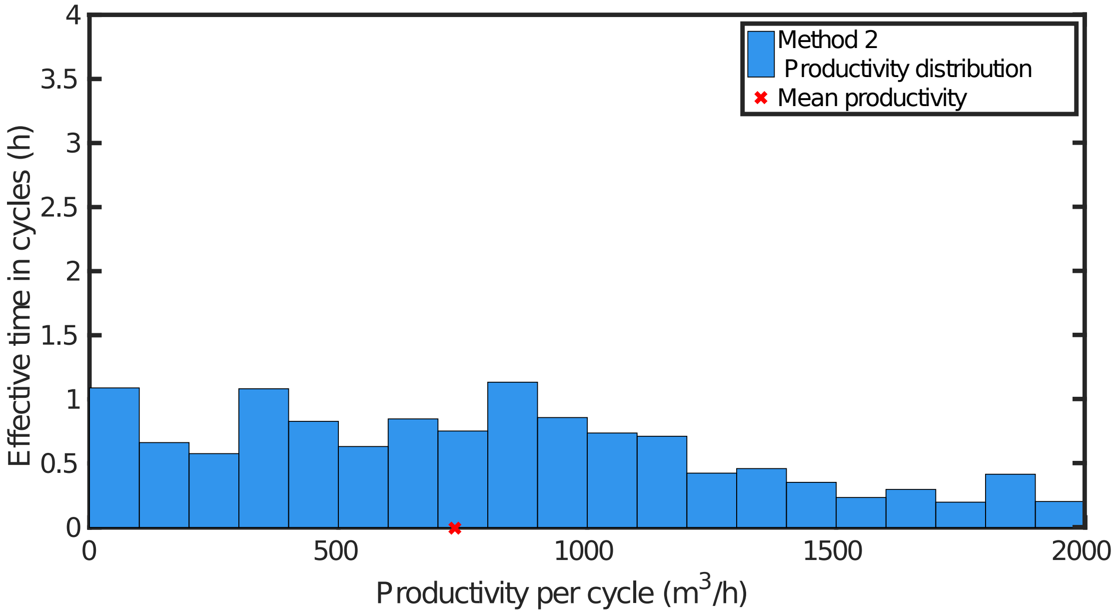


Figure 2.21: Computed-from-measurement per-cycle productivity in Zone 2.

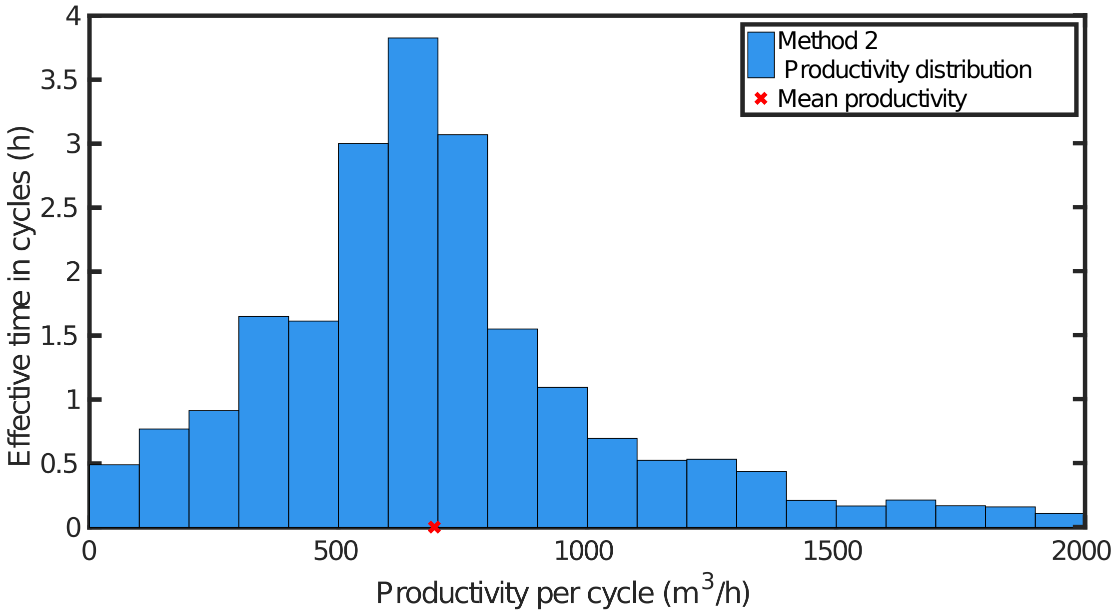


Figure 2.22: Simulated per-cycle productivity in Zone 2.

Method 3

Figures 2.23 and 2.24 compare the productivity while completing Method 3.

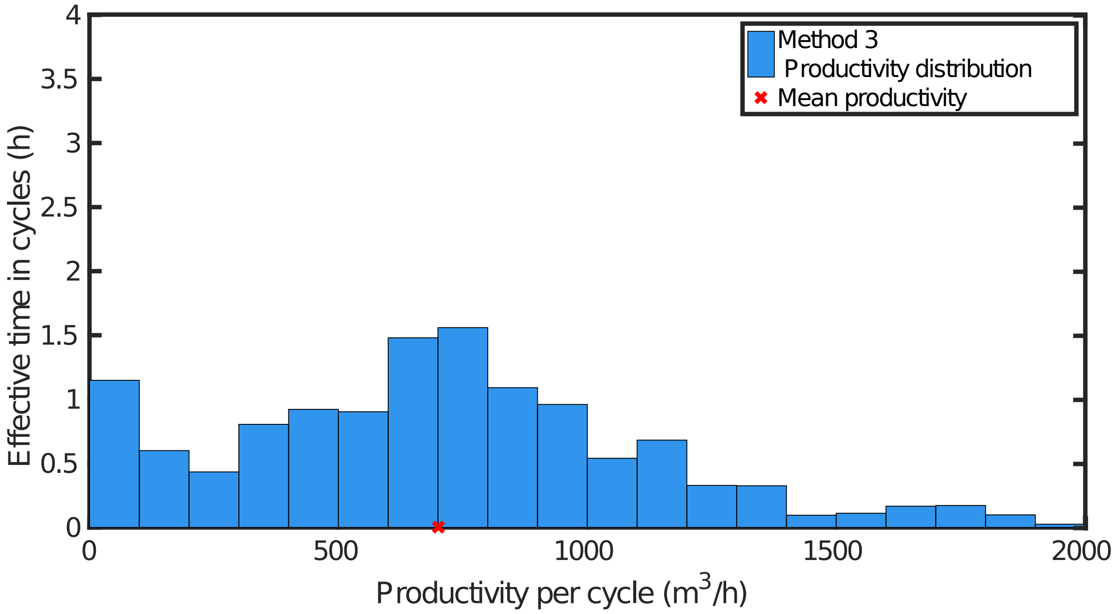


Figure 2.23: Computed-from-measurement per-cycle productivity in Zone 3.

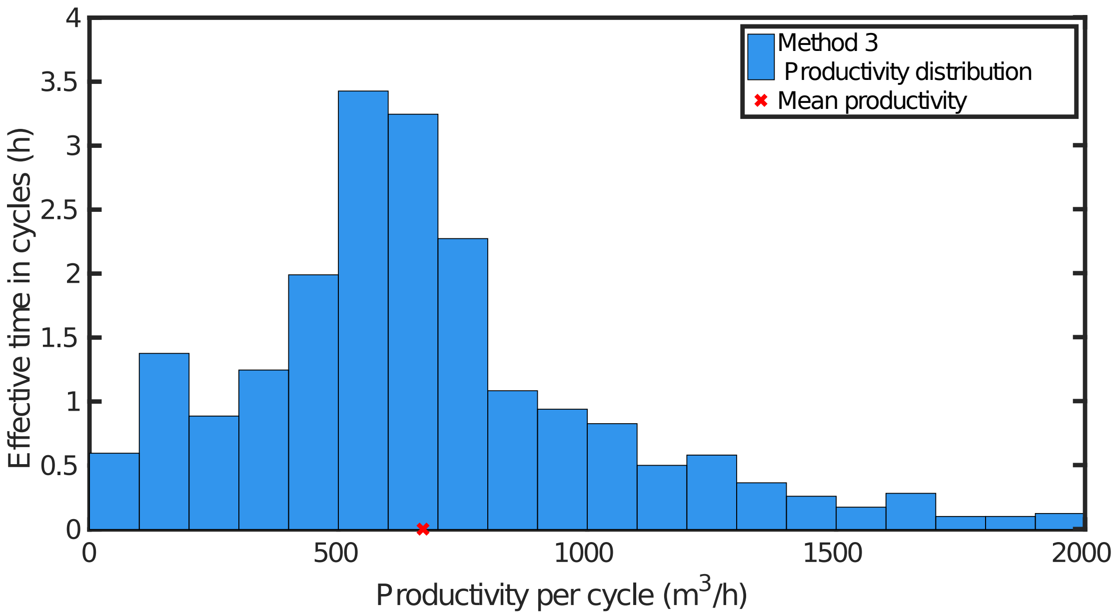


Figure 2.24: Simulated per-cycle productivity in Zone 3.

Table 2.2 summarizes Figs. 2.19 to 2.24 by comparing the mean per-cycle productivity values between measurement and simulation. The difference between the measured mean and simulated mean is expressed as a percentage of the measured mean.

Table 2.2: Mean per-cycle productivity.

Method Number	**Measured Mean (m^3/h)**	**Simulated mean (m^3/h)**	**Difference (m^3/h)**	**Difference (%)**
1	690	660	-30	-4.3
2	735	690	-45	-6.1
3	705	685	-30	-2.8

Appendix D gives plots for the range of velocities, grades and volumes moved under simulation compared to those computed from measured data. Two general observations come from this appendix:

- The velocity of travel used in the simulated operation is less than what was measured (see Table 2.3).
- The mean volume moved per cycle in simulation is greater than what was measured (see Table 2.4).

Table 2.3: Mean velocity summary of figures shown in Appendix D.

Method Number	**Measured Mean Reverse (m/s)**	**Simulated Mean Reverse (m/s)**	**Difference Reverse (m/s)**	**Measured Mean Reverse (m/s)**	**Simulated Mean Reverse (m/s)**	**Difference Forward (m/s)**
1	-1.85	-1.47	**-0.42**	1.13	0.93	**-0.20**
2	-1.90	-1.45	**-0.55**	1.10	0.91	**-0.19**
3	-1.94	-1.44	**-0.50**	1.18	0.91	**-0.27**

Table 2.4: Mean volume moved per cycle summary of figures shown in Appendix D.

Method Number	**Measured Mean Volume (m^3)**	**Simulated Mean Volume (m^3)**	**Difference (m^3)**
1	26	29.5	**0.27**
2	28	30.5	**0.34**
3	24.7	28.5	**0.41**

It is likely that the micro-scale deviations arise from differences in mission execution logic between manual operators and the Tactical Planner component of the Simulation Framework. The logic which dictates when and how the bulldozer executes a slot bulldozing cycle is taken directly from the use case document included as Appendix A. The use cases were developed to represent the ideal laws behind pivot push however in practice it appears that these ideals may not always hold.

A deeper investigation into these discrepancies is outside the scope of this thesis, however this will be a necessary task for future development. Further work would likely include; (i) identifying any systematic discrepancies between the real manual operation and what is expressed in the use case document; (ii) implementing these changes to planning logic used in the Tactical Planner; (iii) conducting simulations with this new planning logic and comparing these results with that of manual operation to determine if the modified logic is more representative of manual operation.

Summary

The aim of this chapter was to validate predictions of the pivot push simulation framework by comparison against data recorded during an experimental trial. The trial consisted of three zones, and within each zone, a different pivot push method was tested. Aerial terrain surveys were used to measure the productivity of a bulldozer as it worked within these three zones. The measured productivity was compared to what was predicted by simulating the operation beginning from the initial surveyed terrain. The data collection was interrupted on several occasions which led to some of the effective time spent in zone not being measured. The effect of these losses was estimated to within a reasonable uncertainty, and flagged as such in the time measurement for affected periods.

We draw the following conclusions:

- The simulation framework predicts the macro-scale rate of production and much of the observed error is thought to be due to issues encountered in the execution of the trial. Results presented in Chapter 4, where better control on the experimental method was achieved, show that the predictions are within the range of survey measurement error. This gives confidence that the pivot push simulation framework is fit for the purpose of predicting the overall production rate of a pivot push operation.

- The micro-scale characteristics of each simulated bulldozer action are less aligned with measurement. As a result, the operations evolve differently between measurement and simulation. The task of evaluating and fixing the underlying reasons for these micro-scale discrepancies is ongoing.

The next chapter uses the validated pivot push simulation framework to predict which method is most productive for a range of strip geometries.

CHAPTER 3

Evaluation of the productivity of pivot push methods

This method is best
the most efficient there is
like the other ones

Introduction

Chapter 2 used experimental data to validate the predictions made by the pivot push simulation framework, allowing it to be applied to a broader range of applications. This chapter addresses the thesis aim *use a validated simulation framework to identify how to most productively execute pivot push bulldozing*. A better understanding of how the chosen method affects overall productivity will be used to inform the selection of methods to implement as part of the Caterpillar semi-autonomous tractor system. The pivot push simulation framework described in the previous chapter is used to predict the most productive method within several different strip geometries.

The haiku that prefaces this chapter speaks to the lack of consensus among miners about how best to implement pivot push bulldozing. Different operators employ different methods, and interviews with industry experts [Medland, 2015; Nott, 2015; MECMining, 2015; Baitch, 2015] revealed each to be a strong advocate of their preferred method. Those interviewed based their preference on experiential arguments yet none was able to provide evidence supporting one method over the others. While it is accepted that experience provides a strong guide as to what works and what doesn't, the lack of consensus suggests the need for deeper investigation.

The aim of this chapter is to establish if one of the methods trialled in Chapter 2 is more productive than the others. This question is, of course, more subtle than it first appears. The productivity of a pivot push operation also depends on the geometry of the strip and the properties of the material being pushed.

The methodology used to determine the preferred method is to predict the performance of the three pivot push methods for different strip geometries. Simulation is used because it enables different methods to be compared side-by-side. The productivity of pivot push is dependent on the distance and grade at which the bulldozer must travel, and these are dictated to a large extent by the geometry of the strip. The geometry features such as depth of overburden, depth of void, and shape of the blast, can vary significantly between strips and even along the length of a single strip. Variation arises through natural undulation in the geology of coal deposits and with randomness introduced by blasting of the overburden. Obtaining a true and unbiased comparison is therefore difficult through experiment, as each method must necessarily be completed in a different location and would be subject to different geometry which may favour or hinder productivity.

The cast-doze-excavate method of mining, of which pivot push is a component, is most commonly implemented in mining operations with overburden depth of less than 50 m [Dyer and Hill, 2011]. The pivot push component of this operation removes overburden to a depth of 20-25 m, with any remainder taken by excavator. Beyond these depths, the economics are such that pivot push is a less attractive option compared to other methods e.g. by dragline strip mining [Humphrey and Wagner, 2011]. These considerations are used to bound the strip geometry in which the pivot push capabilities of SATS would reasonably be deployed.

Methodology

The methodology of this chapter is to compare predicted production rates for each of the three methods over a range of different strip geometries. Simulation took place within environments which were based on pivot push strips at Wilpinjong colliery. Five zones each 36 m in length were selected for comparison. The three methods were simulated in each zone, and compared using the predicted production rate which was obtained. The starting point for the simulation was set from an aerial survey of the strip which was taken after the overburden had been blasted. The end point was defined by the strip design with a target cutting profile at the top of coal. The depth of overburden gradually increased for each zone so that the geometry in each zone was different.

The three methods were compared by the overall productivity defined as the rate of material volume moved to prime per unit of effective time. Productivity is most easily visualized as a *production curve* which is generated as described in the previous chapter. The method which achieved completion (all material volume moved to prime) in the least time is considered to be the most productive method for that zone.

Figure 3.1 illustrates the layout of each zone used in the simulated comparison. Zones are configured to behave as *formicariums* (or ant farms) with material constrained to remain within the zones. The walls of the formicarium conceptually perform the same role as adjacent slots in an actual operation, by constraining the flow of material laterally. The edges of the outermost slots align with the edges of the zone. Slot walls separate all other slots and material can flow into adjacent slots within the zone. Dividing the strip into zones that are completed in isolation was done to avoid loss of resolution in results that might occur if the simulation was conducted over the entire strip.

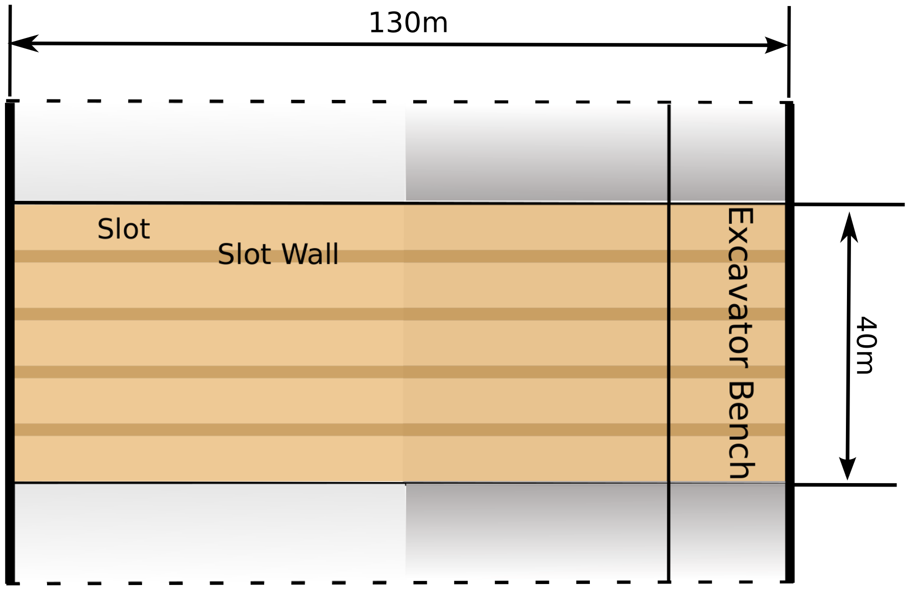


Figure 3.1: Arrangement of slots and slot walls in the zone.

The importance of the formicarium constraint is indicated in Figs. 3.2 and 3.3. Figure 3.2 shows material spilling into adjacent, un-pushed slots under simulation when the formicarium constraint is not present. The consequence is that less material remains within the target zone. In an actual operation the front of the tip head is advanced uniformly across the strip and material within a slot is unable to flow laterally because it is supported by the adjacent material. Figure 3.3 shows the progression with the formicarium constraint, and is a more realistic representation of actual pivot push.

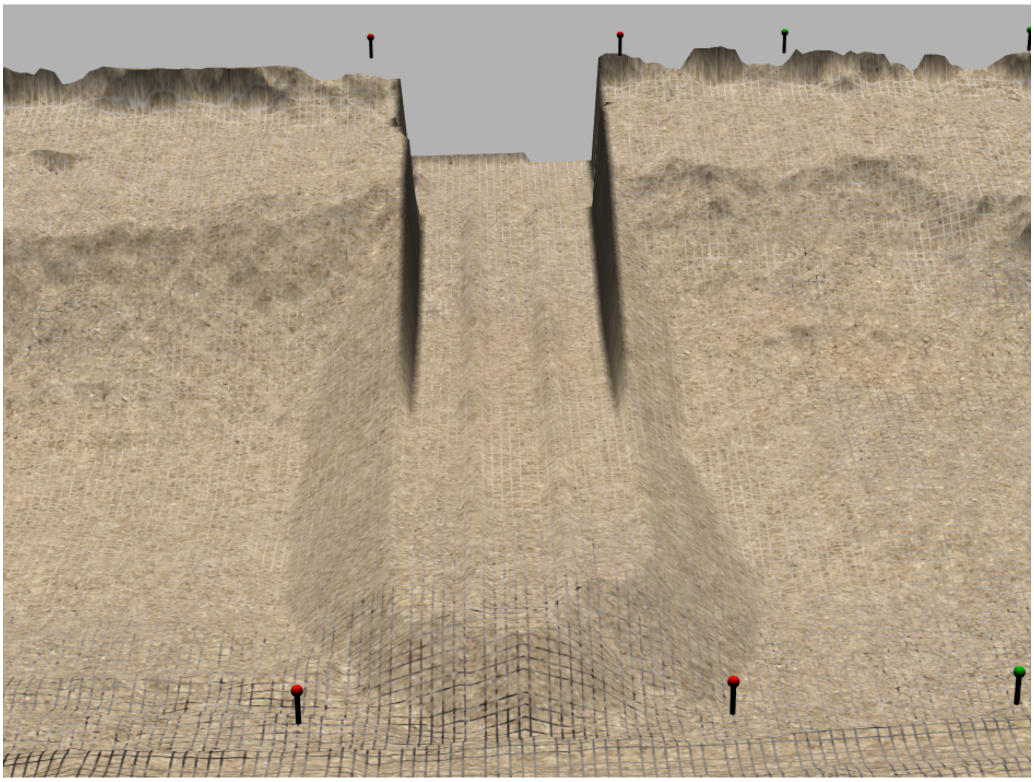


Figure 3.2: Material spilling from the edge of the simulated zone. This is seldom seen in reality as all slots within a strip are progressed consistently. The effect of the material spillage is that the front of the tip head advances more slowly as material spills to the sides as well as the front of the dump.

Figure 3.3: The simulated pivot push occurring within a slice of terrain in the strip. No material is able to leave the workspace.

The Terrain Simulator was configured such that the simulated material did not swell or compact in response to the work of the bulldozer. The total material volume contained within the zone remained constant throughout the simulation. Note also the work of this chapter assumes the material properties are consistent with those experienced during the trial described in Chapter 2. These material properties are used within the simulation to establish push volumes and track slip were calibrated from those trials [Bettens, 2016].

Strip geometry of the zones which were tested

The geometry of the five zones tested was based upon a production strip at Wilpinjong colliery. Figures 3.4 to 3.8 show a representative cross section of each of the five zones. Each zone has a progressively deeper overburden. The void depth remained relatively constant as this is controlled by the geology of the deposit being mined which does not vary significantly within a single strip. Each zone was also subject to a unique starting terrain profile which was created by the chaotic effects of the overburden blast.

Zone 1

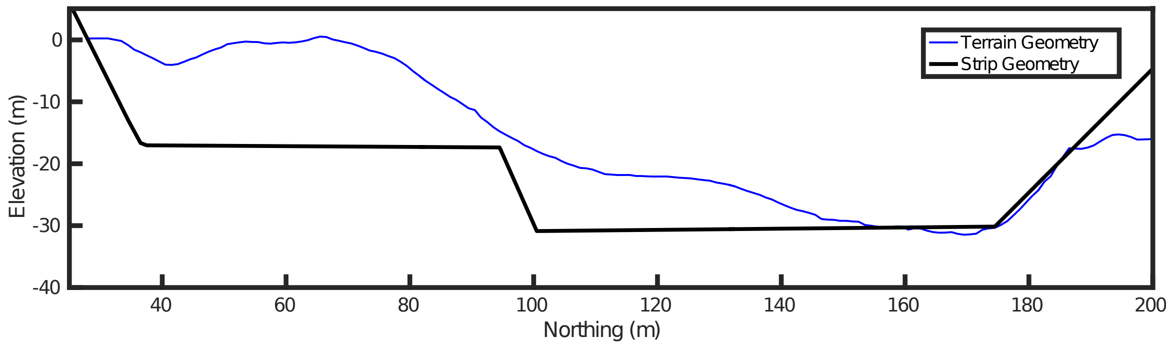


Figure 3.4: Initial geometry of zone 1.

Zone 2

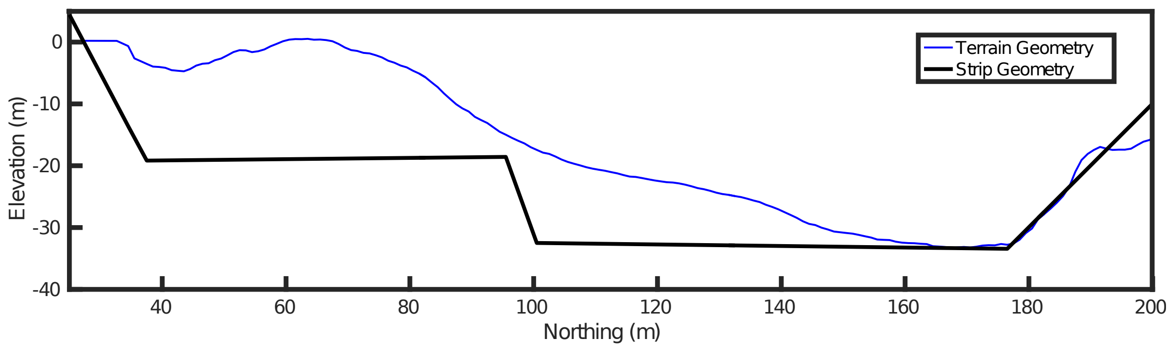


Figure 3.5: Initial geometry of zone 2.

Zone 3

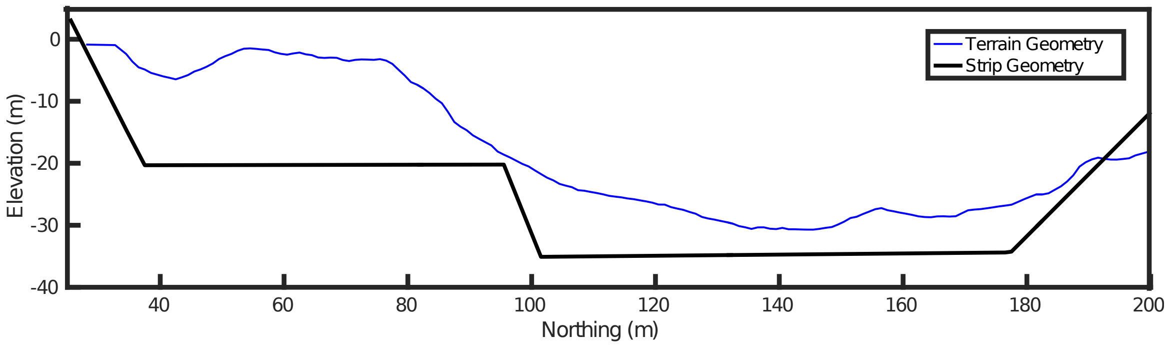


Figure 3.6: Initial geometry of zone 3.

Zone 4

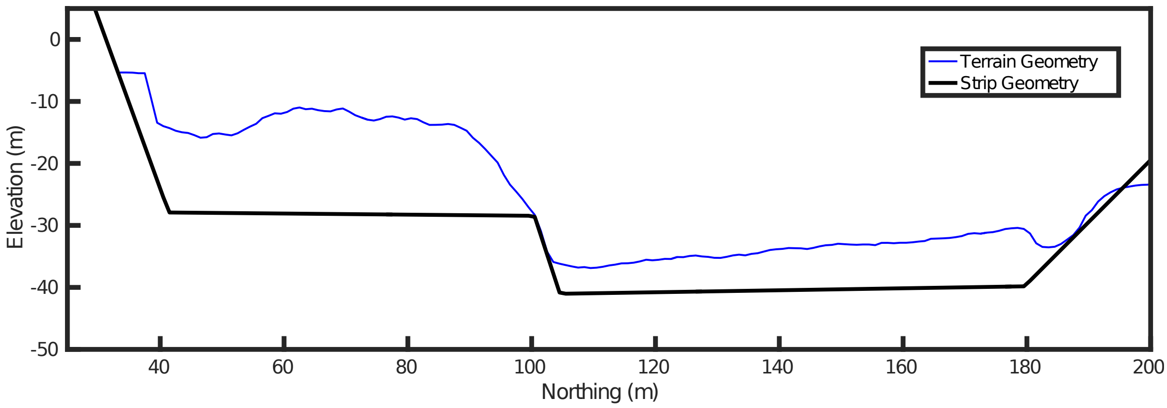


Figure 3.7: Initial geometry of zone 4.

Zone 5

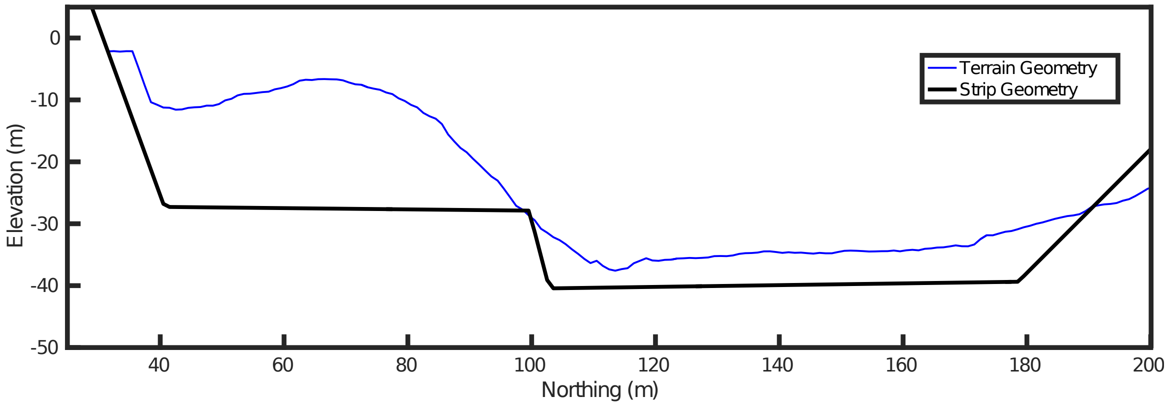


Figure 3.8: Initial geometry of zone 5.

Table 3.1 summarizes the above figures with the key dimensions of each zone. Overburden depth is calculated as the mean depth from the pre-blast profile to top of coal. Void depth is calculated from the average depth of the bottom of the void from a horizontal plane extending from the edge of the top of coal. Centroids are calculated at the centre of the difference between the initial and final terrain maps.

Table 3.1: Zone geometries

Zone number	**Overburden depth (m)**	**Void depth (m)**	**Centroid Removed (x,z)**	**Centroid Added (x,z)**	**Distance between centroids (m)**	**Grade between centroids (%)**
1	17.4	13.1	(62.8, -9.28)	(151.3, -21.9)	89.40	-14.26
2	19.8	14.0	(62.5, -10.8)	(152.4, -22.6)	90.67	-13.13
3	20.9	14.4	(61.8, -12.3)	(150.1, -22.2)	88.85	-11.21
4	21	13.1	(70.0, -20.8)	(148.9, -29.1)	79.34	-10.52
5	24	12.3	(69.5, -17.8)	(145.8, -29.1)	77.13	-14.81

Results

Figures 3.9 to 3.13 show the production curves generated for all three methods within each of the five zones.

There is a similar trend in Zones 1, 2 and 3, wherein Methods 2 and 3 are quite closely matched, and that Method 1 is noticeably less productive than both. Interestingly in Zones 4 and 5, the productivity of all three methods is very closely matched. As Zones 4 and 5 had a deeper overburden than the other zones, this may suggest that the productivity of Method 1 decreases for shallower overburden.

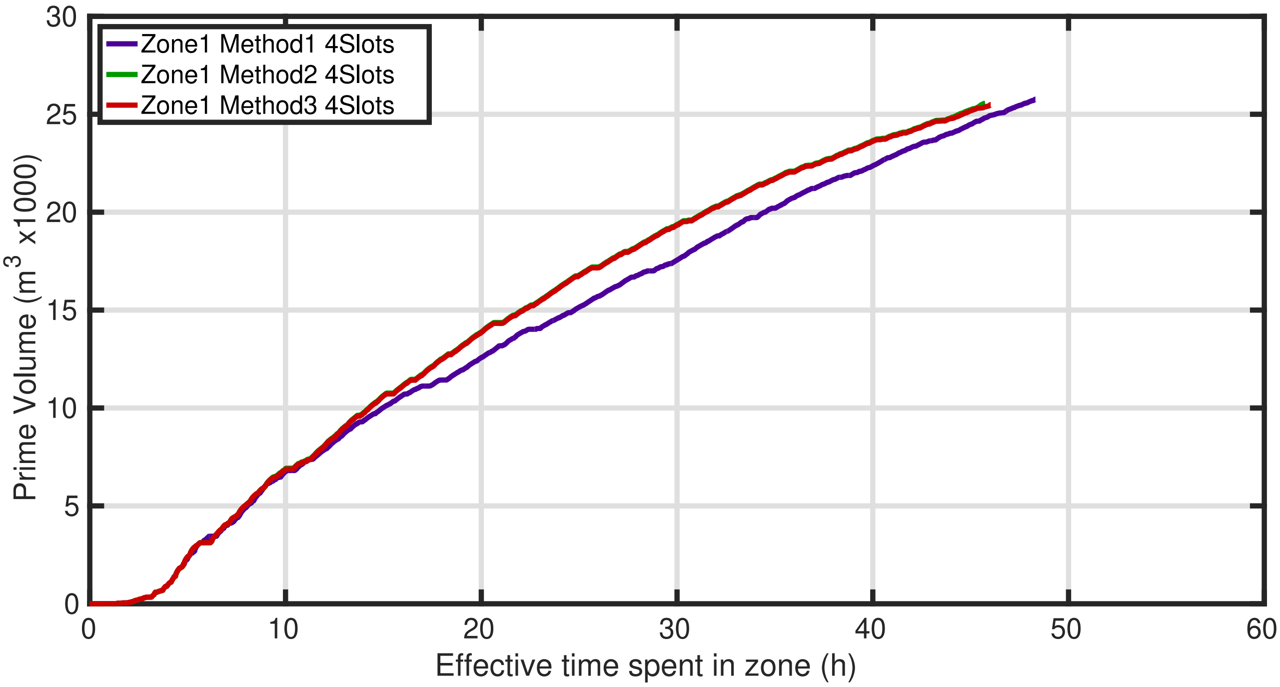


Figure 3.9: Zone 1 method productivity comparison.

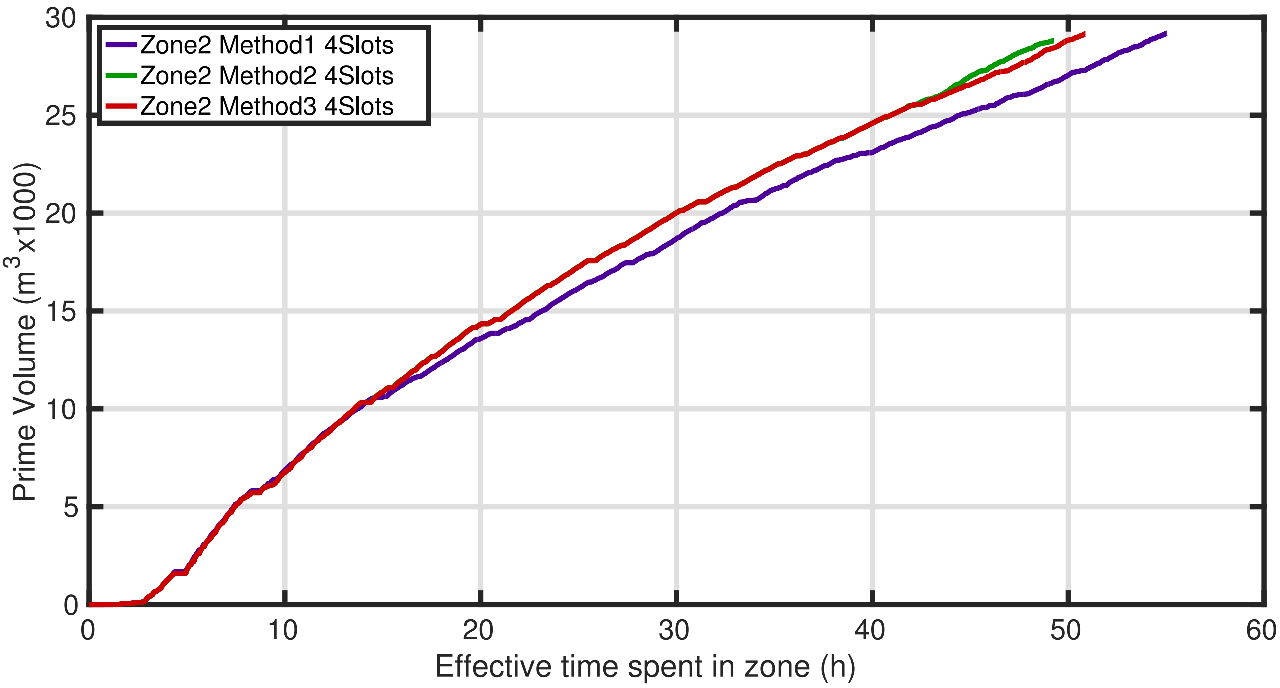


Figure 3.10: Zone 2 method productivity comparison.

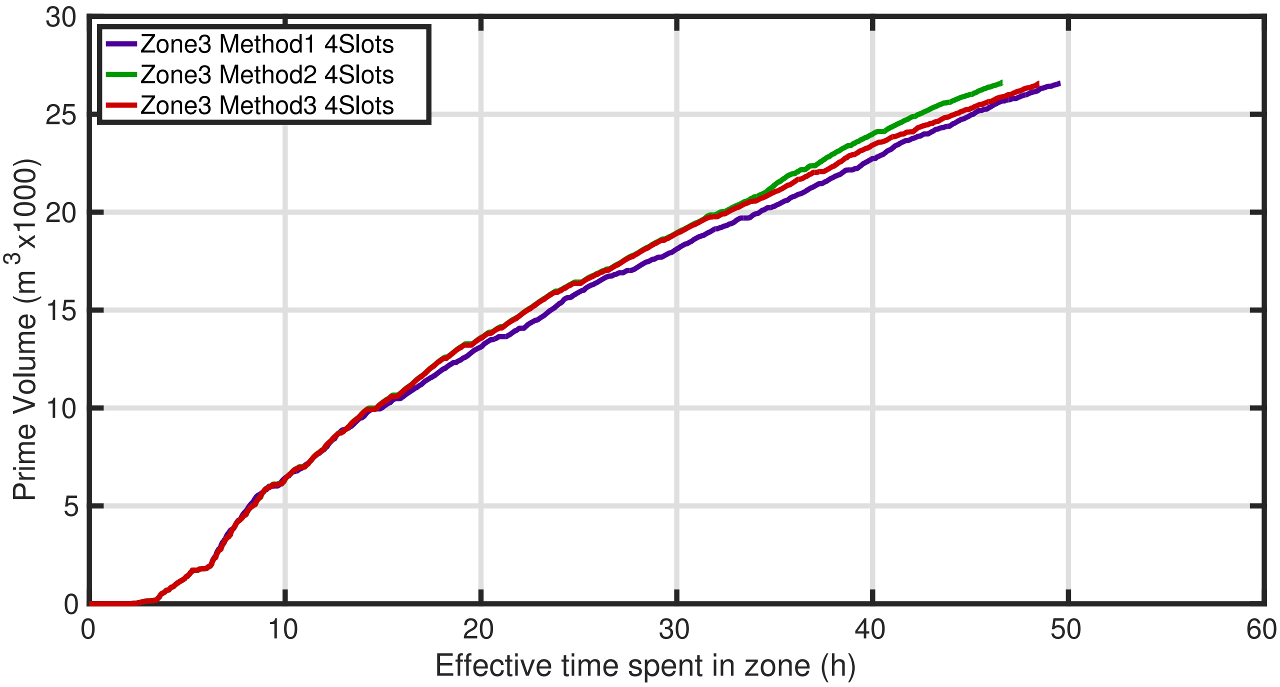


Figure 3.11: Zone 3 method productivity comparison.

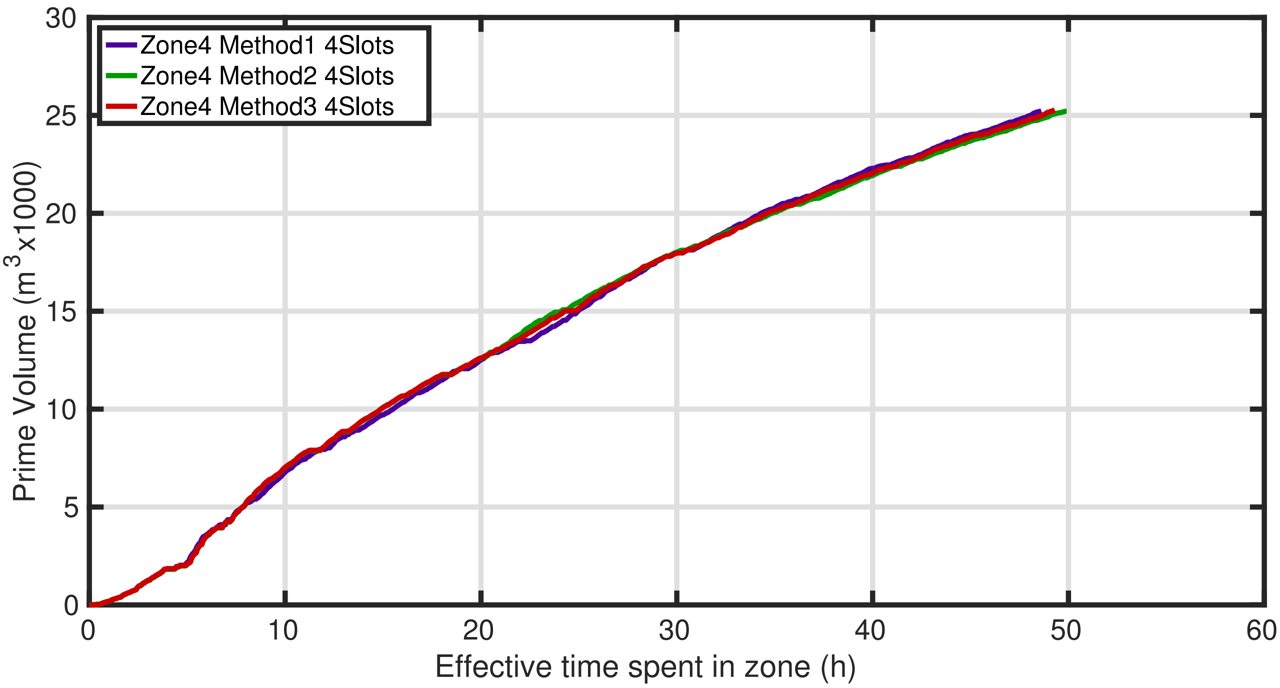


Figure 3.12: Zone 4 method productivity comparison.

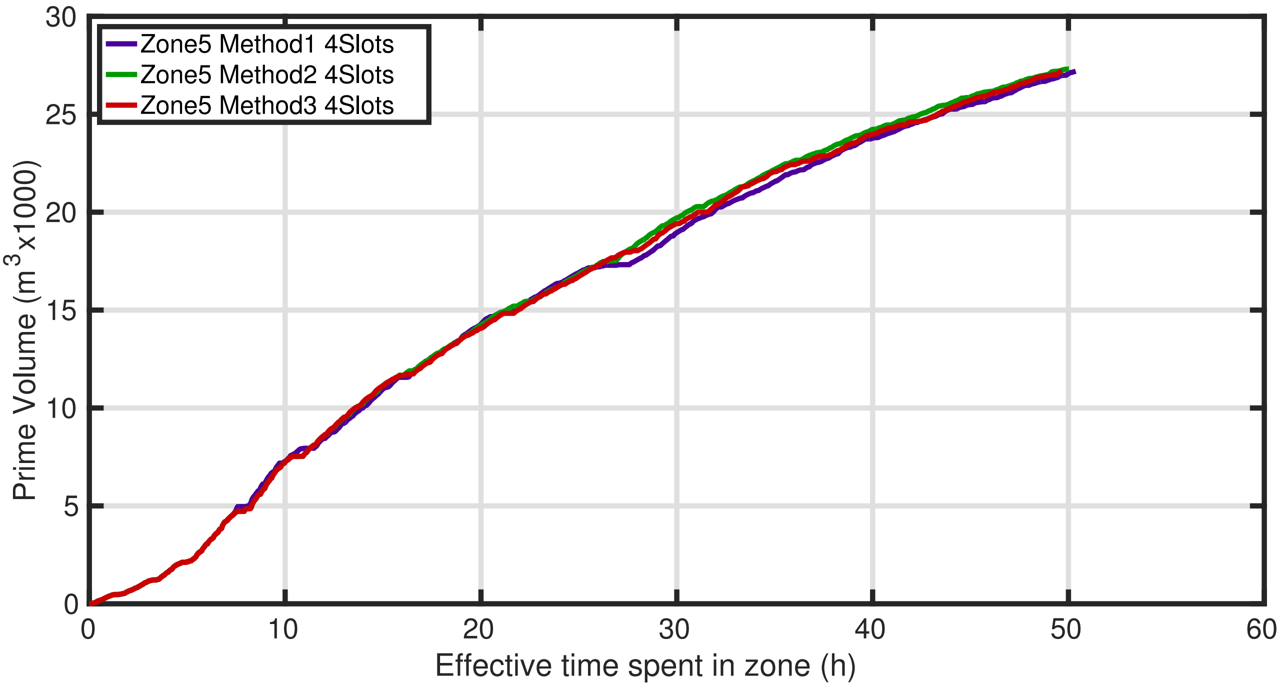


Figure 3.13: Zone 5 method productivity comparison.

We determine the overall 'most productive' method across the five zones. Each method is ranked based on its productivity relative to other methods within each zone. The productivity of a method is benchmarked by its performance relative to other methods within the same zone. The same volume is moved for each simulation within a zone, so the productivity of each method is simply represented by the time spent in effective effort. A reference time is computed from the average time spent for the three methods, and each method is then compared against the reference. An overall representation of a method's performance is calculated as the sum of the time differences between that method and the reference for each of the five zones.

Table 3.2 summarizes the production curves, providing the overall time taken for each method and the mean time recorded in each zone.

Table 3.2: Time spent for each method in the five zones.

	Method 1 time (h)	Method 2 time (h)	Method 3 time (h)	Mean time in zone (h)
Zone 1	48.3	45.5	45.9	46.57
Zone 2	54.9	49.8	50.8	51.83
Zone 3	49.6	46.6	48.4	48.20
Zone 4	48.5	49.9	49.1	49.17
Zone 5	50.3	50.0	49.6	49.97

Table 3.3 presents the difference between each method and the mean of that zone. In this calculation, a negative total time indicates less time to complete the same task as other methods. The differences between the productivities of each method are relatively small in relation to the total time of the operation in question. The result of this analysis is that Method 2 is marginally more productive than Method 3 and that Method 1 is marginally less productive than Methods 2 and 3, however, it should be noted that in many of the test cases, there was no significant difference between the productivities of the three methods.

Table 3.3: Difference from measured time to reference for each method in the five zones.

	Method 1 difference from mean(h)	Method 2 difference from mean (h)	Method 3 difference from mean (h)
Zone 1	1.73	-1.07	-0.67
Zone 2	3.07	-2.03	-1.03
Zone 3	1.40	-1.60	0.20
Zone 4	-0.67	0.73	-0.07
Zone 5	0.33	0.03	-0.37
Total	**5.87**	**-3.93**	**-1.93**

Summary

The aim of this chapter was to determine how to most productively pivot push from among the three methods identified in Chapter 2. The simulations presented have been conducted to inform the decision of which would best be implemented under the Caterpillar semi-autonomous tractor system. The validated pivot push simulation framework was used to predict the productivity for three candidate methods within a range of different strip geometries. Five different zones were used, all based upon the geometry of strips at Wilpinjong colliery. Each of the methods was ranked by its performance relative to an average reference generated for each zone.

We draw the following conclusions:

- Methods 1, 2 and 3 are all very close in the productivity simulated for each of the test cases here.
- Method 2 may be said to be marginally more productive, however the difference between the most productive and least productive methods identified here is small.

Other considerations

This section is included as an addendum to the chapter, and describes some of the other considerations surrounding the selection of a preferred pivot push method. These considerations are external to the work described in this thesis.

The experience of industry experts consulted [Medland, 2015; Nott, 2015; Baitch, 2015] was that material compaction occurs when the weight of the machine repeatedly passses over dumped material. Material compaction is thought to support higher productivity as more loads of material can be placed into the void before uphill pushing is required. Experimental results presented in this thesis regarding material compaction proved inconclusive, so no evidence based argument can be made here to support these claims. It was, however, intuitively reasoned that if compaction was to occur, greater compaction should occur for back stacking (Methods 1 and 3) than for tip heading (Method 2) because each consecutive layer is traversed by the bulldozer. The effect of material compaction was not simulated due to computational complexity, and a lack of data from which to determine a method-specific compaction rate.

Method 3 was ultimately chosen to be implemented as part of the Caterpillar semi-autonomous tractor system. The rationale behind this decision was that while simulation suggests Method 2 may be marginally more productive, the productivity difference between any of the methods is small, and the effect of material compaction was not considered in the simulation.

The next chapter uses experiment to compare the semi-autonomous tractor system implementation of Method 3 against manual operation.

CHAPTER 4

Comparison of semi-autonomous and manual pivot push

Driverless dozers
to move earth efficiently
must improve further

Introduction

Chapter three established that in a comparison of three methods, Method 3 was preferred when assessed on productivity. This chapter evaluates the effectiveness of semi-autonomous pivot push using an implementation of Method 3. Specifically, the chapter compares the semi-automated system relative to manual execution through experimental trial.

Effectiveness in this setting has two components: (i) the productivity measured as the rate of material volume moved per unit of effective time within the strip; and (ii) the percentage of effective time per unit of available time.

The work of this chapter focuses on a single semi-autonomous bulldozer under the supervision of one operator. The findings will be used to guide further development and improvement of the system as it progresses from a research project to a commercial product with multiple machines working simultaneously.

Overview of the production trial

The trial executed to measure the effectiveness of SATS (the SATS trial) was conducted over a five week period from 9 November to 14 December 2016 at Wilpinjong Colliery. The trial was structured to compare the operation of manual and SATS in terms of: (i) productivity measured by volume moved to prime per hour of effective time; and (ii) effective time spent working in the trial strip measured as a percentage of available time. A production strip with layout as shown in Figs. 4.1 and 4.2 was dedicated to the study.

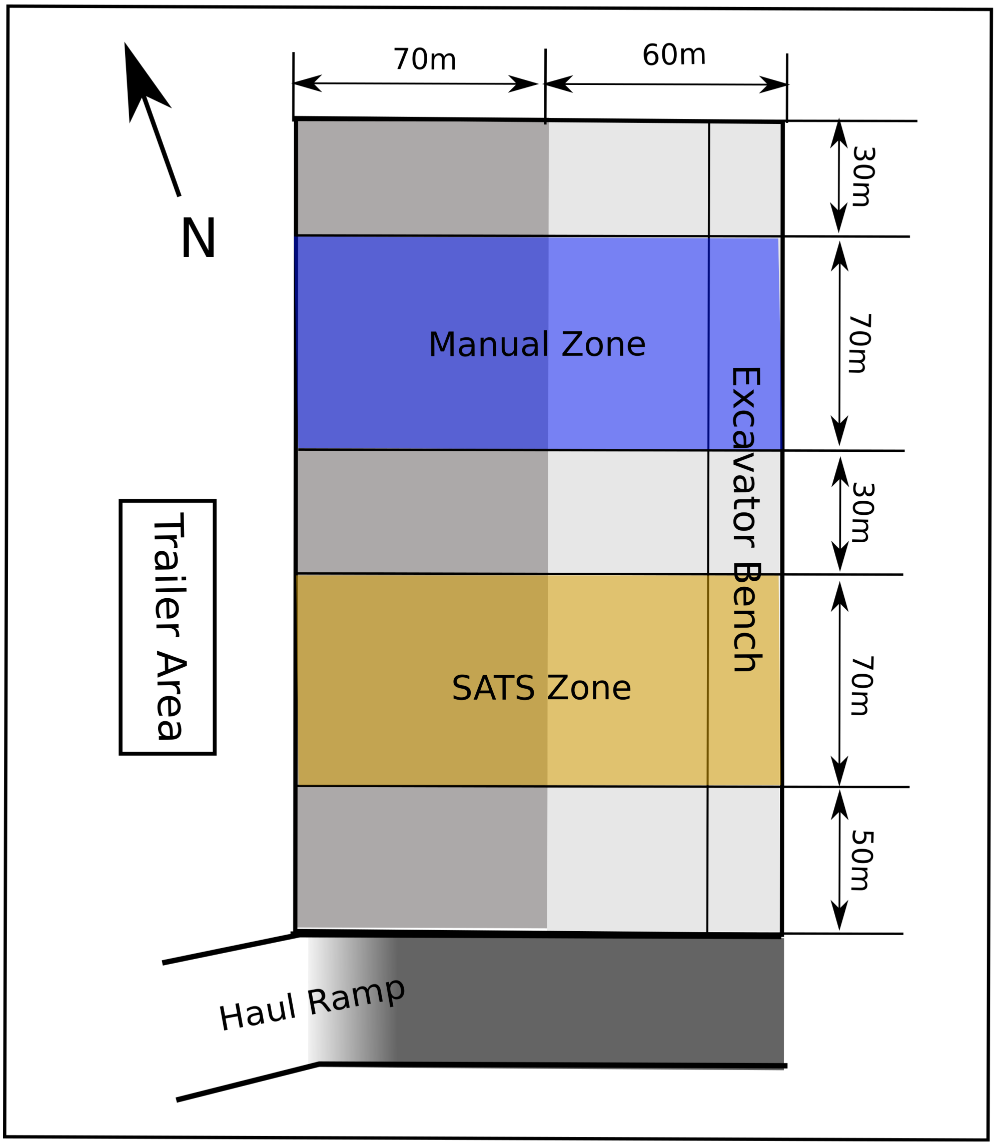


Figure 4.1: Plan view of the experimental strip for the semi-autonomous trial. The manual zone was worked exclusively under manual operation, and the SATS zone exclusively under semi-autonomous operation. The plan-view area of each zone was 9100 m^2. The experimental protocol allowed areas outside of the Manual or SATS zones to be worked either under manual or SATS operation as convenient.

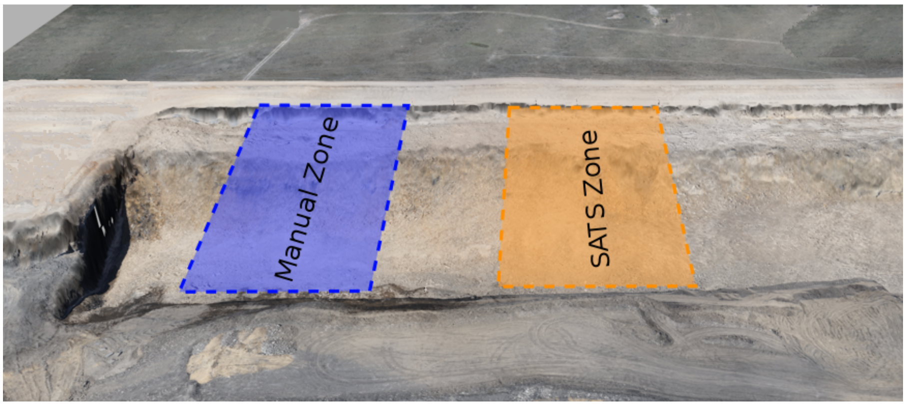


Figure 4.2: Three-dimensional view of the SATS trial strip obtained from terrain survey taken just after the blast.

Bulldozer 2010 was outfitted with the necessary additional sensors and computing hardware required for autonomous operation using the Caterpillar Command for Dozing system [Caterpillar, 2012], but remained manually operable. A remote operator station was installed in a demountable trailer located on the strip low wall. Bulldozer 2010 was also equipped with the Leica Jigsaw JDozer fleet management system [Leica-Geosystems, 2013], used by the site to monitor task activity and capture production time and maintenance delays. A full list of data channels recorded on-board the machine is provided in Appendix D.

Two 70 m long zones were identified in the strip, see Fig. 4.1, and both zones were worked exclusively by Bulldozer 2010 for the duration of the trial. The first zone, termed the *manual zone*, was worked in conventional fashion with the operator on board the machine. The second zone, termed the *SATS zone*, was worked using the semi-autonomous capabilities with the operator located at the remote operator station. Buffer areas between and either side of these zones were worked by a mix of manual and semi-autonomous operation as convenient. The productivity evaluation presented in this chapter relates only to work done in the manual and SATS zones.

Method 3, described in Chapter 2, was used as the pivot push method across the entire strip.

The volume of material moved to prime was measured by aerial terrain surveys which were taken throughout the trial period using the methodology described in Appendix B. A total of 45 surveys were captured throughout the trial. These will be referred to by the names Survey-1 to Survey-45. Effective time was accumulated whenever the bulldozer was in motion within the zone. This included time spent productively moving material and relocating between slots but excluded time where the bulldozer was idle.

The productivity in a zone was evaluated by its deviation from predictions of the simulation framework. This methodology was used to control the influence of strip geometry, which varied along the length of the trial strip. The simulations were conducted under the same strip geometry as the measured operation, such that any differences in the productivity of measurement and simulation must be related to the manner in which the machine was operated.

The percentage of available time spent in effective effort was determined by monitoring the *equipment status* throughout the entire trial, primarily using the JDozer fleet management system installed on the machine. The analysis drew also from data logged by the Caterpillar Command For Dozing system and observations made during the trial to help resolve ambiguities. A full list of the possible equipment statuses provided by JDozer is given in Appendix D. The JDozer system required the operator to manually update the machine's status when switching between tasks. For example, when transitioning from a transit activity to a production activity, the operator was required to update the status of the machine to 'prime push production' using a touch screen interface. The mode of operation (either manual or semi-autonomous) was noted at all times during the trial so that a breakdown could be generated for manual and semi-autonomous operation individually. Equipment status monitoring occurred throughout the entire trial period.

Swapping from manual to semi-autonomous (or vice versa) happened when the height difference between manual and SATS zones exceeded allowable values or when all available material had been removed requiring that an excavator pass along the highwall to cut down the excavator bench. Where possible, transitions occurred at a site shift change to minimize the time spent transitioning between modes. Areas outside the manual or SATS zone were completed by either operation method as convenient. Particular care was taken to ensure that any difference in elevation between the manual and SATS zones was gradually transitioned within the 30 m buffer region separating the zones.

The trial began following a preparation task that was completed by a team of three bulldozers which removed the top of the rough undulating terrain of the post-blast strip. This was done to avoid a concern that the uneven terrain could occlude the line-of-sight 2.4GHz wireless data connection between the bulldozer and the command trailer. The initial survey for the trial (Survey 0) was taken after the completion of this preparation task. After the preparation was completed, Bulldozer 2010 worked exclusively in the trial strip for the duration of the trial.

Eight bulldozer drivers operated Bulldozer 2010 throughout the trial. At the commencement of the trial each operator had less than ten hours experience commanding the machine in semi-autonomous mode. The trial therefore involved a significant component of operator learning as they grew accustomed to the control interfaces of SATS. The lack of prior experience was due to the newness of the technology and some unexpected delays in the deployment of the technology due to weather. This learning phase is believed to have had an impact on performance but is confounded with other factors and the impact is difficult to quantify.

A timeline of the SATS trial is shown in Fig. 4.3. Bulldozer 2010 worked within the trial area, alternating between manual command and semi-autonomous command. Small outages of RTK corrections were seen throughout the trial, although these were all short in duration and did not significantly impact the acquisition of data. There was a four-day period near the end of the trial in which no work was completed in the trial area.

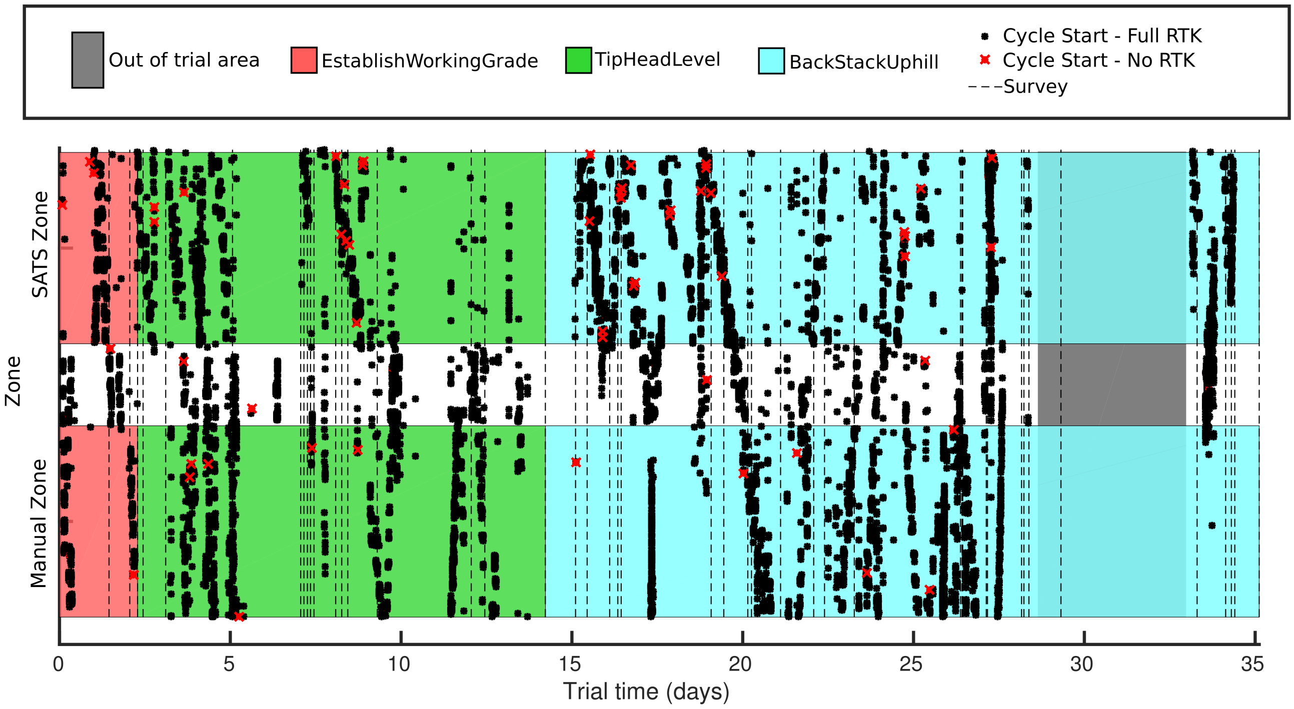


Figure 4.3: A timeline of the SATS trial. The two horizontal coloured bars are used to identify the phase of the operation in each zone. The colouring represents the progression of the push. The trial was conducted so that transitions between activities, i.e. between establishing the working grade and tip heading to level, occurred at the same time. Circular markers represent the location of Bulldozer 2010 within the strip at the beginning of a cycle. Red markers indicate the GNSS RTK corrections were lost at some time during the cycle.

Figures 4.4 and 4.5 chart the total volume of material contained within each of the zones for the duration of the trial. Although the range of survey measurement uncertainty appears significant at this scale, it is apparent that the material contained within the SATS zone was compacted by approximately 5% and the volume of material contained within the manual zone was compacted by approximately 1.5% throughout the duration of the trial.

The difference in compaction between the manual and SATS zone is thought to be related to water within the strip and specifically within the SATS zone. The trial occurred following an extended period (approximately six weeks) of unseasonal rain which left the bottom of the void filled with water prior to blasting of the strip. A non-level geometry along the floor of the void resulted in more water being located in the SATS zone than the manual zone. Material moved to the void by the blast completely covered the pooled water. It is conjectured that the volume of material was inflated by the water which absorbed into it. As this water redistributed itself throughout the course of the trial period, the volume of material in the manual and SATS zones decreased non-uniformly and this resulted in the volume reduction observed in Fig. 4.4.

Simulations described later in the chapter take into account the compaction observed in each zone.

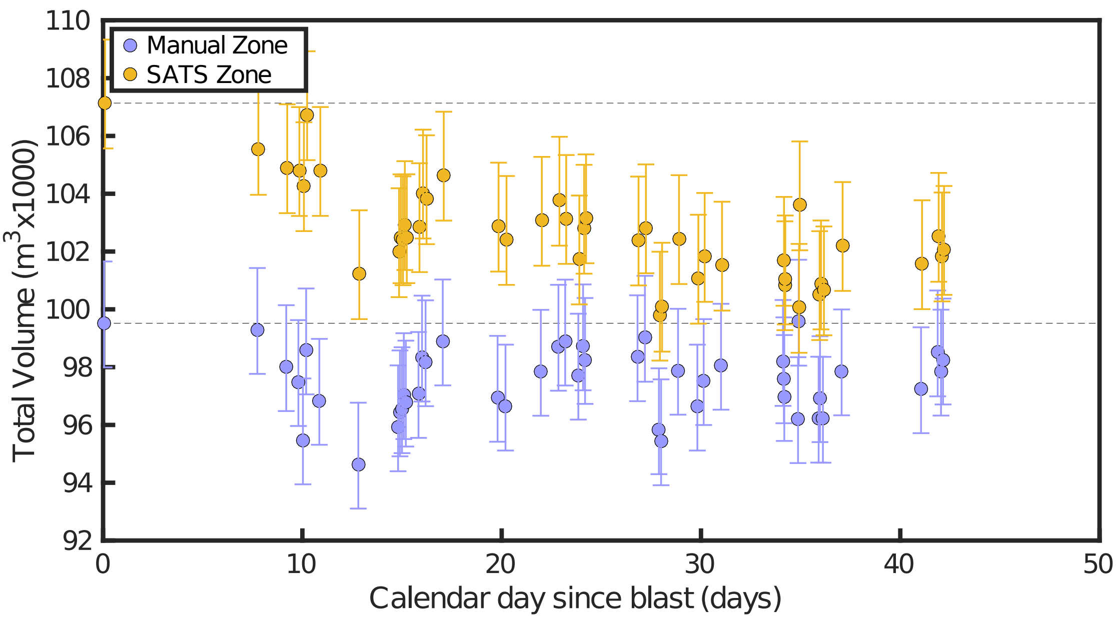


Figure 4.4: Total volume change during the trial.

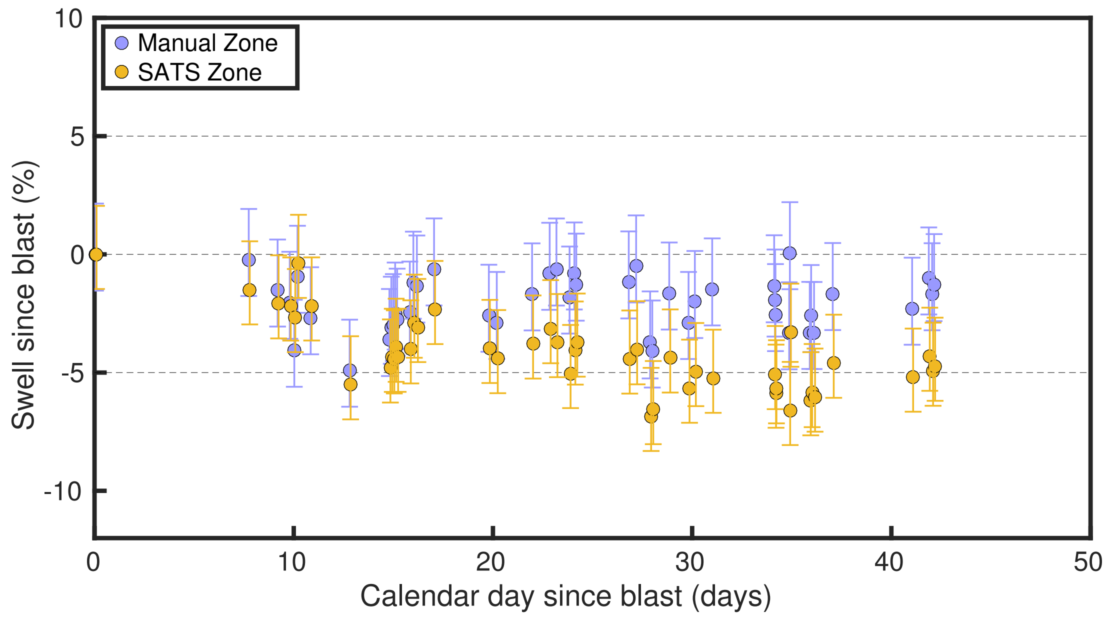


Figure 4.5: Percentage of volume change during the trial. The volume of material in the manual zone decreased by approximately 1.5% and the volume of material in the SATS zone decreased by approximately 5%.

Comparative productivity

This section explores the productivity of manual and semi-autonomous pivot push bulldozing by comparing each against a reference which was obtained using the pivot push simulation framework.

Results

The production curves in Figures 4.6 and 4.7 compare measured productivity to simulated productivity for the manual and SATS zones of the trial strip. The vertical error bars estimate the measurement error of aerial surveys determined using the methodology presented in Appendix B. Note that in both instances the actual push completed before all material was moved to prime. This material remained in a small layer above the coal seam as a precaution against removing any coal.

The productivity measured in the manual zone matches well to the prediction obtained from the simulation framework. This adds strength to the conclusion of Chapter 2 – that the simulation framework gives a good estimate of the manual productivity. The simulated productivity is used as a baseline for the expected manual productivity in the SATS zone against which semi-autonomous operation is compared.

Figure 4.7 shows actual productivity in the SATS zone to be lower than predicted. Specifically, the overall time taken to complete the push under SATS was 20.8 hours longer than predicted or, in percentage terms, approximately 15%.

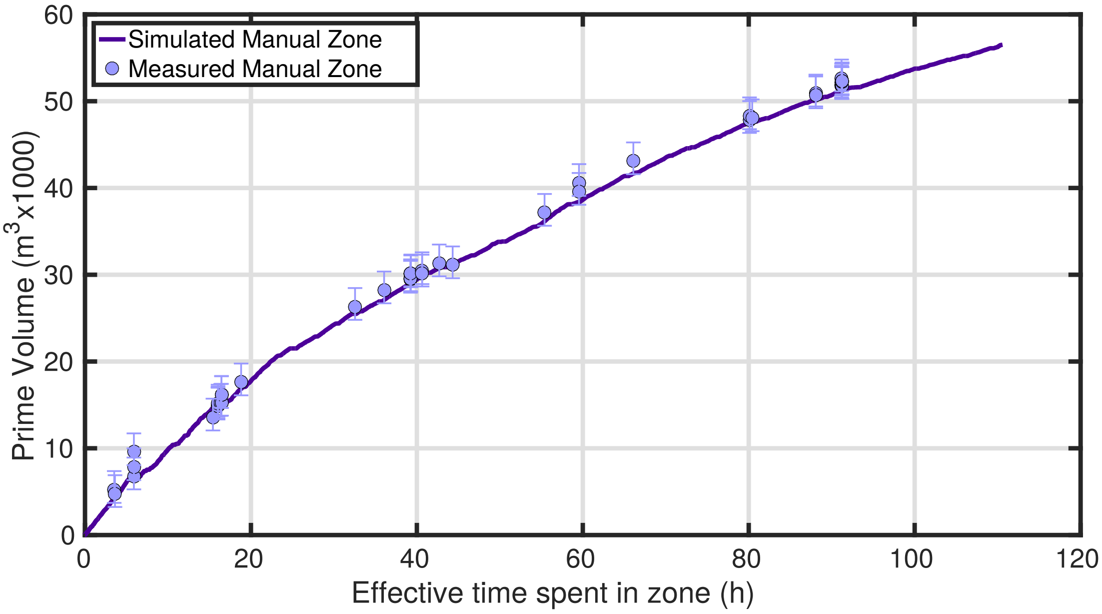


Figure 4.6: Measured productivity compared to simulated productivity in the manual zone.

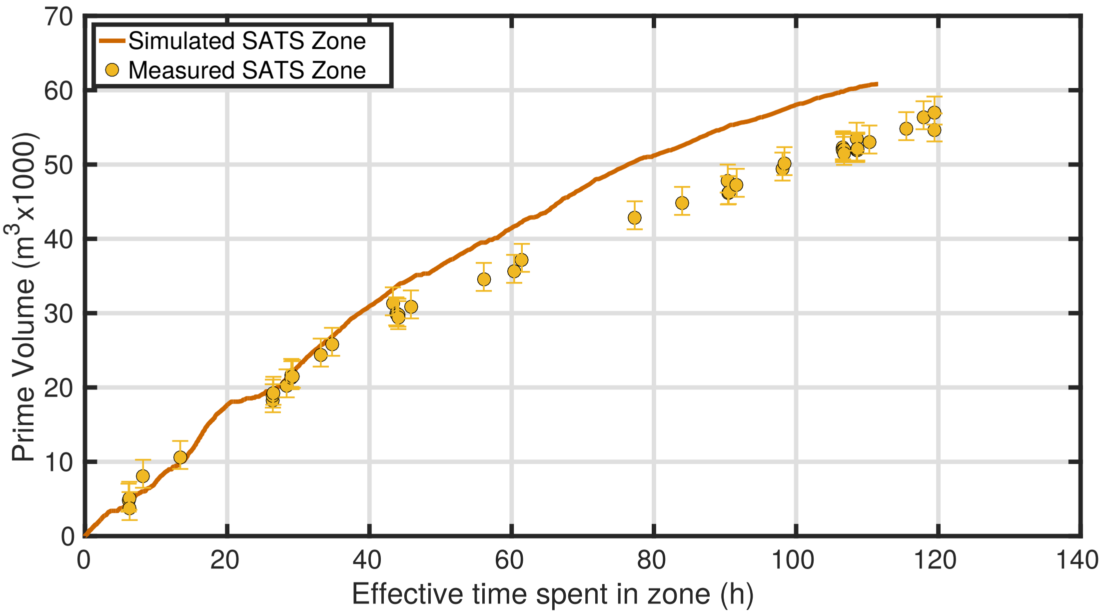


Figure 4.7: Measured production compared to simulated production in the SATS zone.

Table 4.1 summarizes the above figures by comparing the measured and simulated productivity observed in the SATS zone. Not all material was removed from the SATS zone during the trial and the measured production curve terminates slightly below the simulation. Simulated productivity was calculated at the point where the simulated production curve reached a volume of 56,950 m^3 – the total volume moved in the measured operation.

Table 4.1: Summary of productivity results.

	Volume To Prime (m^3)	Time taken (h)	Productivity (m^3/h)
Simulated SATS Zone	56,950	98.3	579.34
Measured SATS Zone	56,950	119.1	478.17
Difference		**+20.8**	**-101.17**

Analysis of lost productivity

We now turn to the question of why productivity under SATS is lower than expected. Specifically we seek to identify the causes of the productivity deficit between what was measured and what was expected from simulation in the SATS zone to identify how this system might be improved.

This is a difficult question to address. Ideally the simulation would be used to identify causes of lost productivity, however as identified in Chapter 2, while the simulation framework correlates well with measured productivity on the macro-scale, discrepancies were found between travelling velocities and per-cycle volumes. Since in what follows these measures are used to identify sources of lost productivity, the methodology used instead is to compare against manual operation. That is to say, while the simulation appears to be a good predictor of the macro-properties of the operation, it is felt that the micro-properties are better examined by comparison with manual operation. Work is planned to refine the simulation framework so that it generates more representative distributions of travelling velocity and volume moved to prime per cycle, however that work has not been undertaken at the time of writing this thesis.

The key argument is, because the manual operation was closely matched with simulation in the macro-scale, the deficit between measurement and simulation in the SATS zone should be identifiable in a comparison between micro-scale aspects of the manual and semi-autonomous operation. There are limits to this methodology (discussed below) and care needs to be exercised.

First, the strip geometry of the two zones was not the same, and the analysis therefore cannot consider aspects of the operation which are likely to be influenced by the geometry. For example, it would be expected that a distribution of travelling distances and grades would be influenced by the geometry of the strip, and a direct comparison between manual and SATS in this regard would not be a fair reflection on the mode of operation. The micro-analysis that follows considers only aspects of the operation that are not dependant on the strip geometry. Furthermore, the analysis focuses on aspects in which SATS is prevented from achieving its maximum productivity due to some identifiable limitation in the configuration of the system.

Second, the issues leading to lost productivity are not independent. For example, the amount of time lost due to the slower reversing velocity of SATS is also increased by the excess distance travelled under SATS. The results obtained here will provide a reasonable estimate of the amount of time which could be saved if each individual issue was targeted in isolation, but the total times identified due to each issue cannot be added to determine the entire productivity deficit. Nevertheless, the various issues can be ranked by the amount of unproductive time which they cause in isolation to prioritize tasks for further development.

For these reasons, the analysis of lost productivity in the SATS zone considers the following: (i) excess travel distance per cycle due to control logic which adds additional reversing distance beyond the next cutting location; (ii) reduced velocity of travel while reversing due to control logic limiting when the machine operates in the second reverse gear; and (iii) time spent in cycles which do not contribute to the production task of adding material to prime.

The methodology adopted is to accumulate the loss of productivity due to a certain aspect of the operation by determining the amount of time that would have been saved had the task been completed in the style of a manual operator. For example, the increased time spent due to the lower reversing velocity of SATS is determined by calculating the amount of time which would have been spent had the bulldozer travelled on average at the velocity observed in the manual zone. The effect of each aspect is considered in isolation. Losses of productivity are calculated as a time increase (in hours) for each aspect of the operation which is considered.

Excess travel distance

As a general principle of pivot push bulldozing, the distance of travel should be minimized in each slot bulldozing cycle. Ideally the bulldozer should begin reversing as soon as the load has been placed to its final location and the machine should reverse only as far as the next identified cutting location. If the machine continues travelling a distance after the load has been dumped, or if the reverse takes the bulldozer beyond the next identified cutting location, this distance must be re-travelled in the other direction until the next cutting location is reached. This adds to the total time of the cycle.

Excess travel distance is defined as the difference between the distance travelled in unproductive activities and distance travelled in productive activities within each cycle. Here, unproductive activities include reversing and re-positioning (forward travel with a raised blade). Productive activities include cutting and carrying. Excess time is the time spent travelling this distance.

It is expected that each cycle will contain some excess of unproductive travel due to *necessary* re-positioning of the machine. Observations of the operation in the manual zone are used to establish how much excess distance is necessary and any more than this amount is defined to be *unnecessary*.

The following assumptions were made in the calculation of excess time: (i) the excess distance is divided evenly between forwards and reverse travel; (ii) the machine travelled in first gear forwards and in first gear reverse when re-positioning. Forward velocity is 0.76 m/s and the reversing velocity is 1.08 m/s as determined from distributions of reverse travelling velocity obtained from experimental data.

Figures 4.8 and 4.9 chart the total time and excess time spent within cycles in which excess distance was travelled. The figures show a distribution of time spent in cycles which contained a certain amount of excess distance travelled. Blue bars represent the total time which was spent in these cycles, and orange bars represent the time which was spent travelling only the excess distance within the cycle.

Both manual and SATS spent time travelling excess un-productive distance, although the proportion of time spent travelling excess distance was greater under semi-autonomous command.

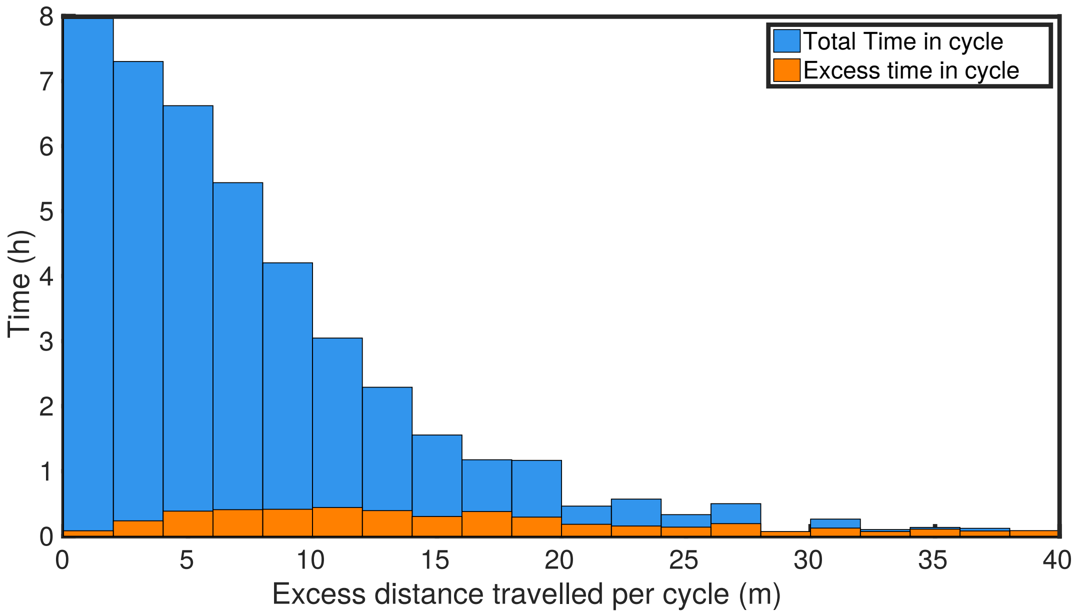


Figure 4.8: Manual Reversing Difference.

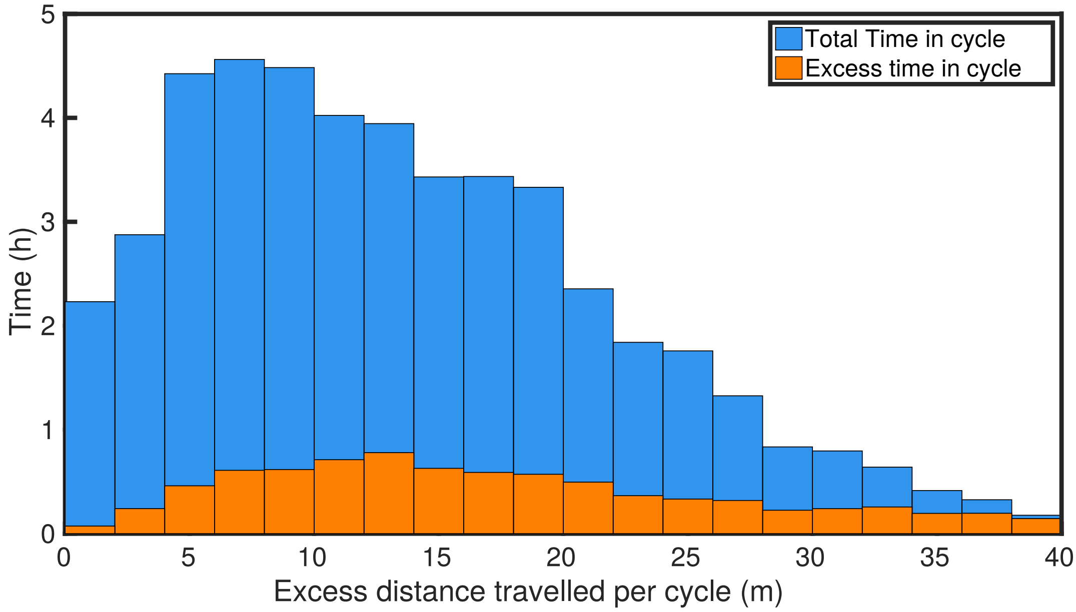


Figure 4.9: SATS Reversing Difference.

Unnecessary excess time is calculated by the following;

$$\Delta T_s = \frac{E_s}{T_s} T_s - \frac{E_m}{T_m} T_s \tag{4.1}$$

Which simplifies to:

$$\Delta T_s = E_s - \frac{E_m}{T_m} T_s \tag{4.2}$$

where: ΔT_s is the added time due to unnecessary excess travel distance, E_s is the excess time measured in the SATS zone, T_s is the total effective time measured in the SATS zone, E_m is the excess time measured in the manual zone, and T_m is the total effective time measured in the manual zone.

Table 4.2 summarizes the above figures, calculating the unnecessary excess time using Equation. 4.2.

Table 4.2: Summary of time lost to excess distance travelled.

Excess time Manual (h)	Excess time SATS (h)	Total time manual (h)	Total time SATS (h)	Added time (h)
4.55	8.05	92.6	119.1	**2.2**

Velocity of travel while reversing

A general principle of pivot push bulldozing is that the reversing velocity should be maximized to reduce the time required to return to the next cutting location. The velocity of travel while travelling unloaded is dependant on the selected gear and the grade of travel. The operator may select either first gear reverse (1R) or second gear reverse (2R).

Manual operators are instructed to travel in 2R whenever possible to minimize time spent without carrying a load. Manual operators only change into 1R if a steep travelling grade necessitates a greater torque applied to the tracks.

The gear selection of SATS is handled by control logic which encodes different conditions for the dumping tactics of tipheading and backstacking. When tipheading, the autonomous system commands the machine to travel at least 12 m from the dump location in 1R before changing to 2R. When backstacking, the autonomous system commands the machine to travel in 1R through the entire dump region until the pivot point has been reached, beyond which point the machine travels in 2R. The control logic limiting travel in 2R is motivated by concerns that the machine is more likely to slide from unstable sections of terrain if travelling faster.

Figures 4.10 to 4.13 compare the reversing velocities in semi-autonomous and manual operation while tip heading and back stacking. It is interesting to note that there are three locations at which ‘peaks’ occur in the velocity distribution. These are located at approximately -2 m/s, -1.5 to -1.7 m/s and -1.1 m/s. Appendix section E.2 contains an analysis of this behaviour and a summary is given here:

- The peak at approximately -2 m/s corresponds with travel in 2R along a level grade.
- The peak located between approximately -1.5 m/s to -1.7 m/s corresponds with travel in 2R at an uphill grade. The slower velocity is due to a reduction in engine speed under increased load. The relationship between travelling speed and load is described by the machines’s *drawbar-pull* curve [Caterpillar, 2010].
- The peak at approximately -1.1 m/s corresponds with travel in 1R. The velocity of travel in 1R is less sensitive to travelling grade, so level and uphill reversing both have a velocity in this range.

Based on the analysis of reversing velocities, we can conclude that manual operators reverse almost exclusively in 2R, while SATS spends a significant amount of time reversing in 1R.

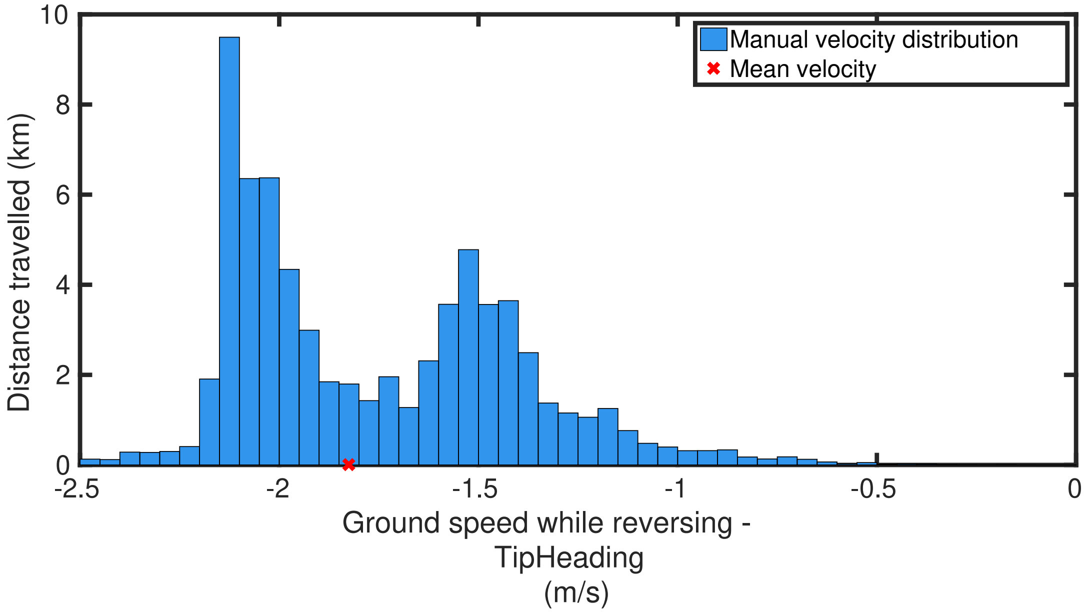


Figure 4.10: Manual TipHeading reversing velocity.

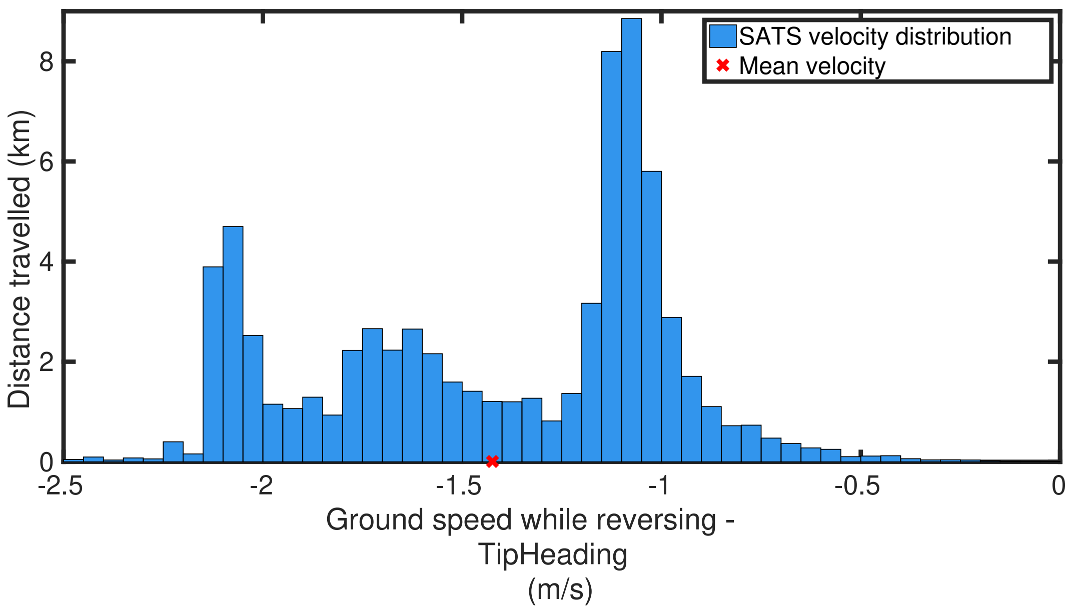


Figure 4.11: SATS TipHeading reversing velocity.

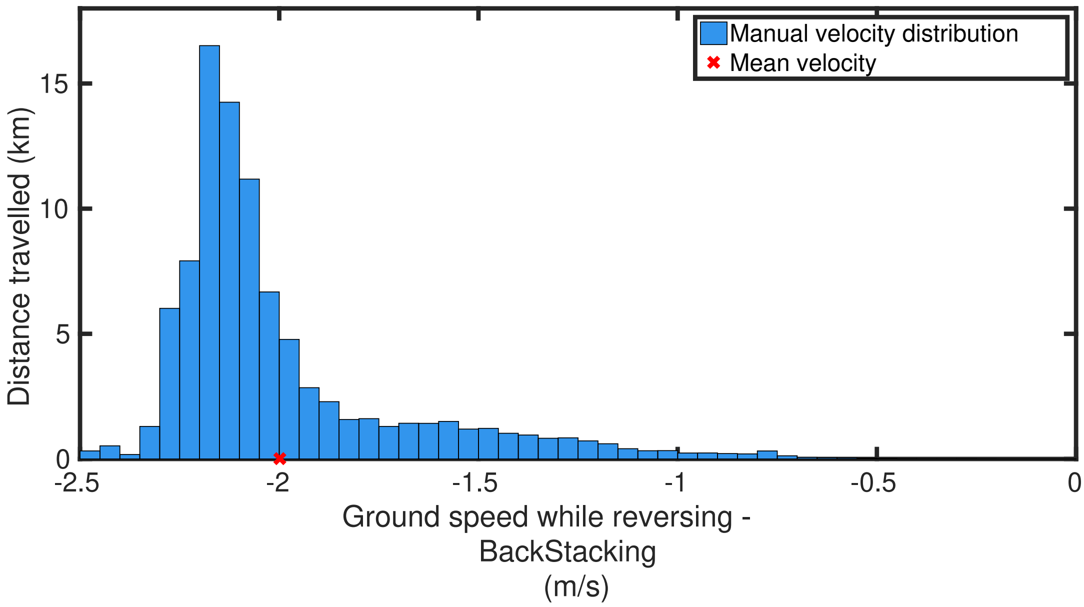


Figure 4.12: Manual BackStacking reversing velocity.

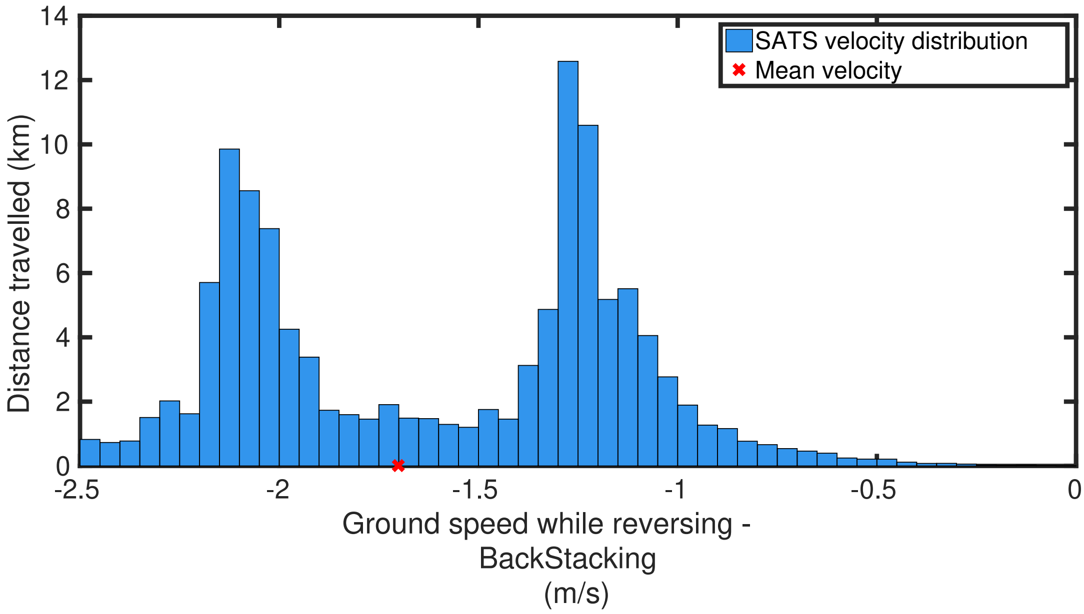


Figure 4.13: SATS BackStacking Reversing Velocity.

The time lost due to the lower reversing velocity of SATS is calculated as;

$$\Delta T_s = \frac{D_s}{v_s} - \frac{D_s}{v_m} \tag{4.3}$$

where: ΔT_s is the unproductive added time due to decreased travelling velocity, D_s is the distance which was travelled while reversing in the SATS zone, v_s is the average reversing velocity in the SATS zone, v_m is the average reversing velocity in the manual zone.

Table 4.3 summarizes the total lost productivity due to decreased reversing velocity under SATS compared to manual. The calculation of time which was lost due to the lower reversing velocity is done individually for tipheading and backstacking, using Equation 4.3.

Table 4.3: Summary of time lost to slower reversing velocity.

	Reversing velocity manual (m/s)	Reversing velocity SATS (m/s)	Reverse distance SATS (m)	Added time (h)
Tip-Heading	-1.83	-1.425	73,062	3.15
Back-Stacking	-1.99	-1.69	125,280	3.10
Total				**6.26**

Unproductive cycles

A general principle of pivot push bulldozing is that each piece of material should only be moved once. Each slot bulldozing cycle should move one load from the overburden region into a prime location. Failure to move material directly to prime, or the movement of material already at prime results in this material being *rehandled*. In this analysis, an unproductive cycle is defined as a cycle in which no new material is moved into the prime region, and encompasses both of these scenarios. Despite not moving material to prime, it is not completely unproductive if material is at least moved some distance towards the prime location. This analysis therefore only considers cycles which do not move material to prime, and are also short in travelling distance.

Un-productive cycles are identified through thresholds on the travelling distance, start location, and end location. The value thresholds are defined based on a coordinate frame which is shown in Fig. 4.14. Un-productive cycles before prime are defined as short-travelling cycles which do not cross into the prime region and are identified by: (i) a forward travel distance less than 20 m; and (ii) a dump location less than 100 m along the x axis (the location of the edge of the coal seam). Un-productive cycles in prime are identified as cycles which move only within the prime region and are identified by: (i) a cut location greater than 100 m along the x axis; and (ii) a dump location location greater than 100 m along the x axis.

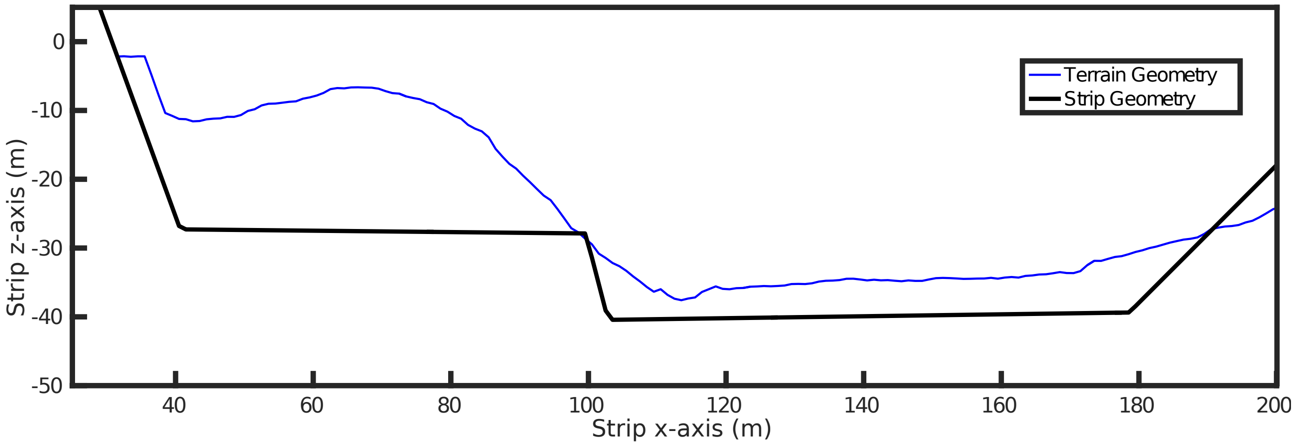


Figure 4.14: Representative geometry of the SATS trial strip.

Unproductive cycles occur from time-to-time for one of three reasons: (i) at the beginning of pivot push before a working grade is established, the bulldozer is unable to dump material directly to prime; (ii) after an excavator has completed a pass to remove material from the highwall bench, it is necessary for the bulldozer to make some short pushes to make the resulting pile of material more traversable; and (iii) if a load of material has been incorrectly placed in the dump region, it may be necessary to make some short pushes to ensure that the slot floor is properly shaped for future traversal. Unproductive time spent while establishing the working grade is not included in this analysis, as this is a necessary component of pivot push. The analysis is therefore divided between the second and third reasons for unproductive work identified above.

As manual operation is used as the control for this experiment, the proportion of time spent in unproductive cycles in the manual zone is taken to be *necessary*, and any more than this proportion is *unnecessary*. It is expected that some operators would be better at this task than others, however because eight different operators regularly rotated through the machine over the course of the trial, it is assumed that the net effect of different skill levels is negligible. The amount of time which was added to the measured SATS operation as a result of unproductive cycles is calculated from the difference between what was seen in the manual and SATS zones.

Figures 4.15 and 4.16 show where unproductive time was accumulated throughout the trial in the manual and SATS zones. The x-ordinate represents distance into the slot from the highwall to the low wall. The y-ordinate represents the total time which was spent in unproductive cycles which had their start location within a certain range. Figure 4.17 summarizes the findings, accumulating the total time spent in unproductive cycles. It is apparent that the semi autonomous system spent significantly more time performing non-productive cycles than a manual operator.

Most of the unproductive cycles observed during the trial were targeted to remove the spoil pile left by the excavator after a pass along the highwall bench. When operating in SATS mode, the operator was required to complete this task using the remote-control capabilities of the system. Operators found this task more challenging when done remotely because of a reduced ability to perceive the machine's environment from the remote station. As a result, the effectiveness of each push was less than would be expected if the operator sat inside the machine, and more time was required to clear the spoil pile.

Remote operation of a bulldozer is an acquired skill, and requires experience to perfect. At the commencement of this trial, the eight operators were very new to the system, meaning that there was a component of learning throughout the trial. It is expected that as these operators become more experienced with remote operation, their skill will duly improve. It was also noted that the difficulty experienced in pushing down the excavator spoil pile could be reduced if the spoil pile was lower. An emphasis should be placed upon the importance of maintaining the height of the spoil pile below reasonable thresholds.

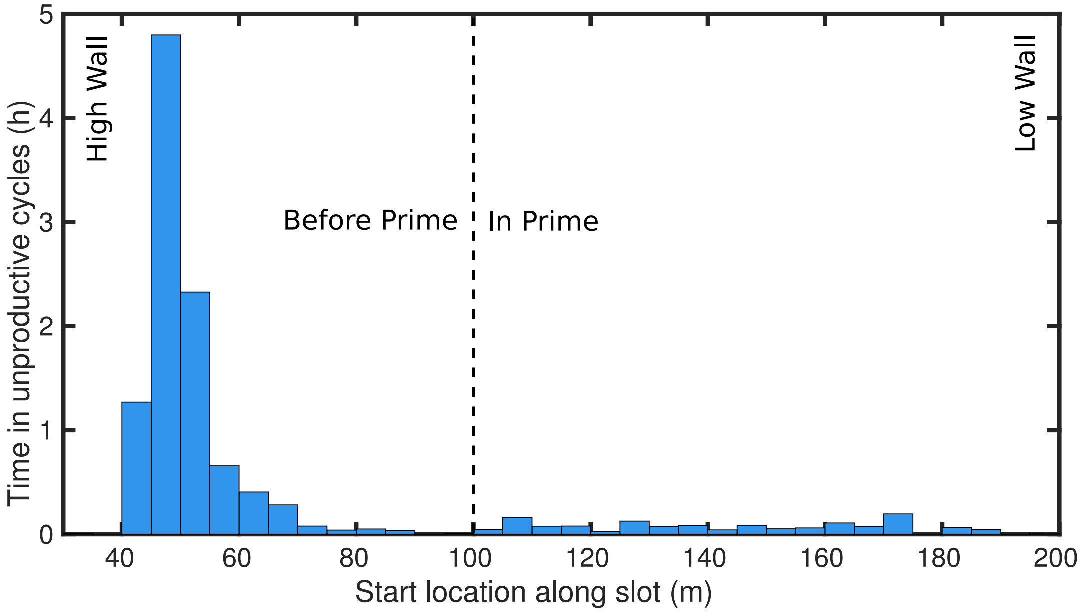


Figure 4.15: Distribution of starting locations of unproductive cycles in the manual zone.

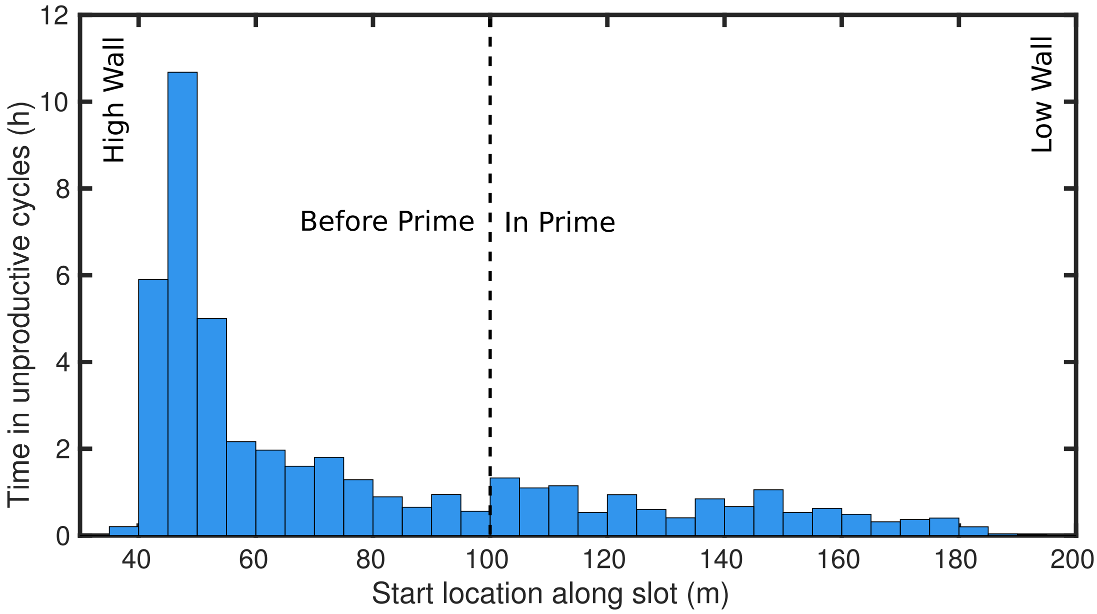


Figure 4.16: Distribution of starting locations of unproductive cycles in the SATS zone.

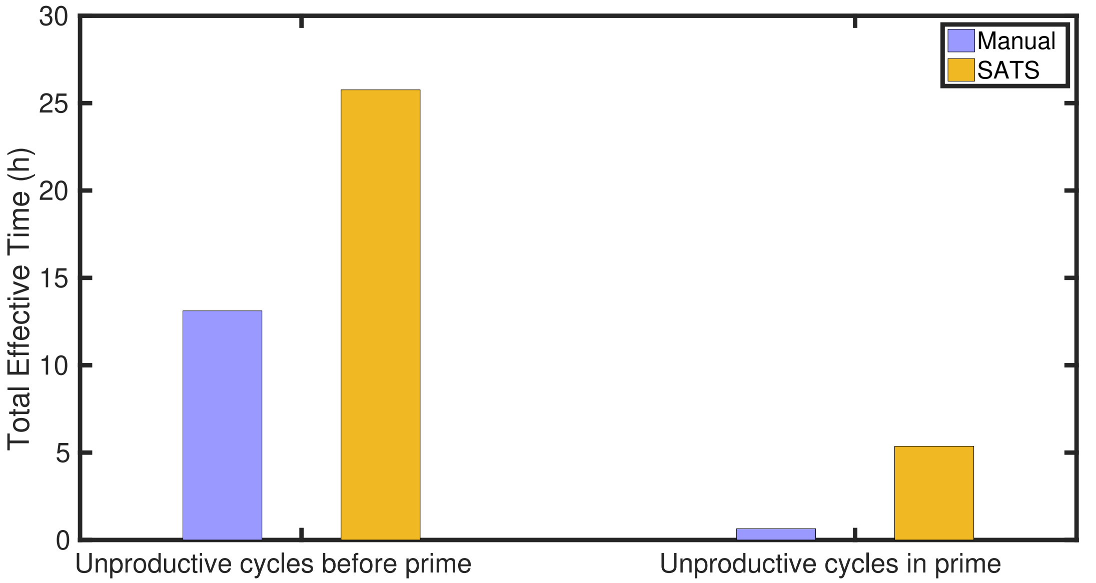


Figure 4.17: All time spent within un-productive cycles before prime and in prime.

Unnecessary unproductive time is calculated by the following;

$$\Delta T_s = \frac{U_s}{T_s} T_s - \frac{U_m}{T_m} T_s \tag{4.4}$$

where: ΔT_s is the unproductive added time due to unproductive cycles, U_s is the unproductive time measured in the SATS zone, T_s is the total effective time measured in the SATS zone, U_m is the unproductive time measured in the manual zone, and T_m is the total effective time measured in the manual zone.

Table 4.4 summarizes the calculation of unnecessary unproductive time using Equation 4.4. A total of 13.36 hours of lost operation were identified among unproductive cycles before prime and in prime.

Table 4.4: Summary of time lost to unproductive cycles.

Mode	Unproductive time Manual (h)	Unproductive time SATS (h)	Total time Manual (h)	Total time SATS (h)	Added time (h)
Before prime	13.11	25.75	92.6	119.1	8.88
In prime	0.64	5.35	92.6	119.1	4.47
Total					**13.36**

Summary of productivity investigation

Table 4.5 summarizes the investigation into lost productivity by collating the times which were gained due to each of the unproductive actions investigated above. These findings suggest that unproductive cycles contributed most heavily to the productivity deficit seen between what was simulated and predicted in the SATS zone.

We refrain from simply adding the times identified for each of the issues. This is because the issues are inter-dependant and a direct addition may lead to some double-counting of time. For example, the amount of time lost due to the lower reversing velocity would have been less if SATS had not also travelled excess distance in reverse. Nevertheless, these results can be reasonably used in the prioritization of further development work.

Table 4.5: Summary of lost production.

Item	Time added (h)
Excess travel distance	2.2
Reduced reversing velocity	6.26
Unproductive cycles	13.36

Time spent effectively working

This section examines how the machine spent its time when under manual and semi-autonomous command. There are four counts of time which are of interest in productivity monitoring: (i) Calendar time; (ii) Available time; (iii) Utilized time; and (iv) Effective time. The aim of this section is to compare manual and SATS in terms of effective time as a percentage of available time.

In this analysis, time categories are divided between *in-trial* and *out-of-trial*. Un-avoidable delays such as routine maintenance or un-predictable delays such as those caused by weather events and temporary evacuation of the strip due to a nearby overburden blast cannot be attributed to either the manual or SATS mode and were therefore considered out-of-trial. Table 4.6 gives a complete list of the time categories which were excluded from the production time comparison. All other times were considered in-trial.

Table 4.6: Definitions of out of trial time.

Time Category	Definition
Unscheduled	An operator is not assigned to the machine.
Routine Downtime	Planned maintenance time.
Maintenence Delay	A delay in maintenance (e.g. waiting for parts or labour).
Weather Delay	Weather conditions cause the machine to temporarily cease work.
Site Process Delay	The operator is called away to operate another machine.
Blasting Delay	Equipment and/or personnel must leave the area for a nearby blast.
Out Of Pit	The machine is not in the vicinity of the trial area.
Non-Trial Time	The machine is otherwise not working under trial conditions (e.g. performing road maintenance work in the vicinity of the trial area).

Table 4.7 defines all delay time categories which detract from effective time whilst working in trial. Electrical Downtime, Mechanical Downtime and SATS Issue time capture the physical reliability of the machine and its resilience to breakdown. Personnel Delay, Operational Delay and Non-Productive Time capture the efficiency of the operator and operations team in ensuring that the machine was utilized when available. Idle time captures the brief pauses and breaks in operation which occurred whilst at work in the trial area. The remainder of actions which do not fall within any of these delay categories constitute the Effective Time category.

Table 4.7: Definitions of in-trial time.

Time Category	Definition
Electrical Downtime	Downtime due to an electrical fault on board the machine.
Mechanical Downtime	Downtime due to a mechanical fault on board the machine.
SATS Issue	Downtime due to any SATS-related fault.
Personnel Delay	Operator bathroom and fatigue breaks.
Operational Delay	Mid-shift breaks and inter-shift changeover time.
Non-Productive Time	Machine in transit to or from the work area.
Idle	Machine idle or parked within the work area.

Results

Figure 4.18 shows a high-level breakdown of how Bulldozer 2010 spent its time throughout the trial period. The trial was punctuated with several day's worth of delay time, where the machine was not working under trial conditions. There were several instances while waiting for an excavator to complete a pass along the highwall that the bulldozer was re-allocated to work in a different area of the mine. Routine maintenance removed the machine from service for a period of 24 hours. External factors also contributed to delay time, such as multiple nearby blasts requiring temporary evacuation of the work area, and a particularly violent thunderstorm which caused the entire mine to pause operation for 6 hours. Of the 823.2 hours of total calendar time logged during the trial, 277.3 hours were spent in manual operation, and 290.1 hours in semi-autonomous operation.

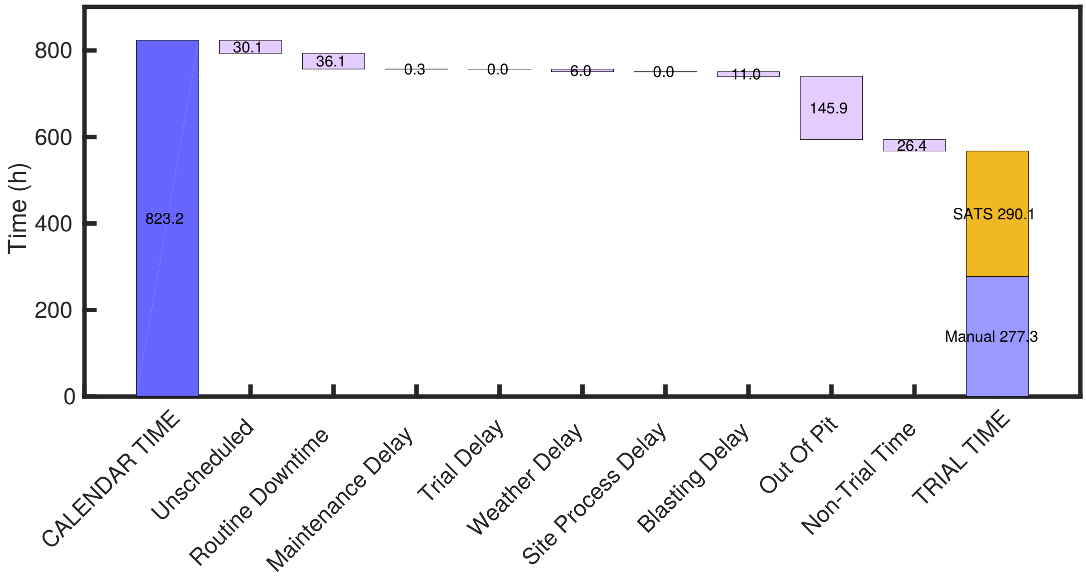


Figure 4.18: Out of trial time breakdown.

Figures 4.19 and 4.20 show the breakdown of trial time in the manual and SATS zones. It was observed that SATS accumulated a lower portion of effective time than manual operation. This was primarily due to the accumulation of SATS Issue time, and the accumulation of Idle time in the work area. Interestingly, SATS spent a lower portion of its time in Operational Delays and Personnel Delays than manual operation.

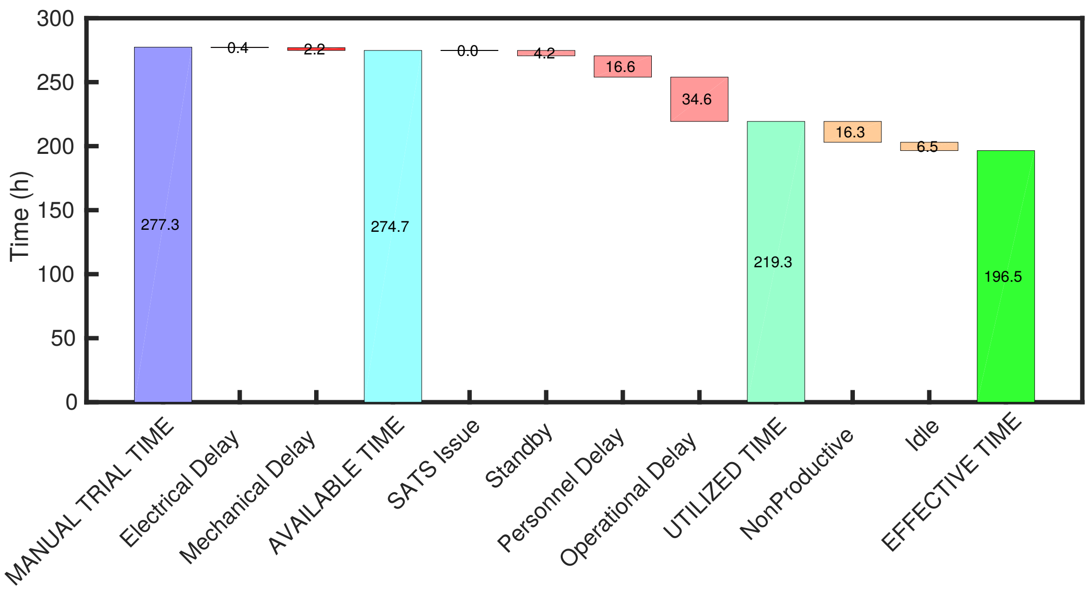


Figure 4.19: Manual trial time breakdown.

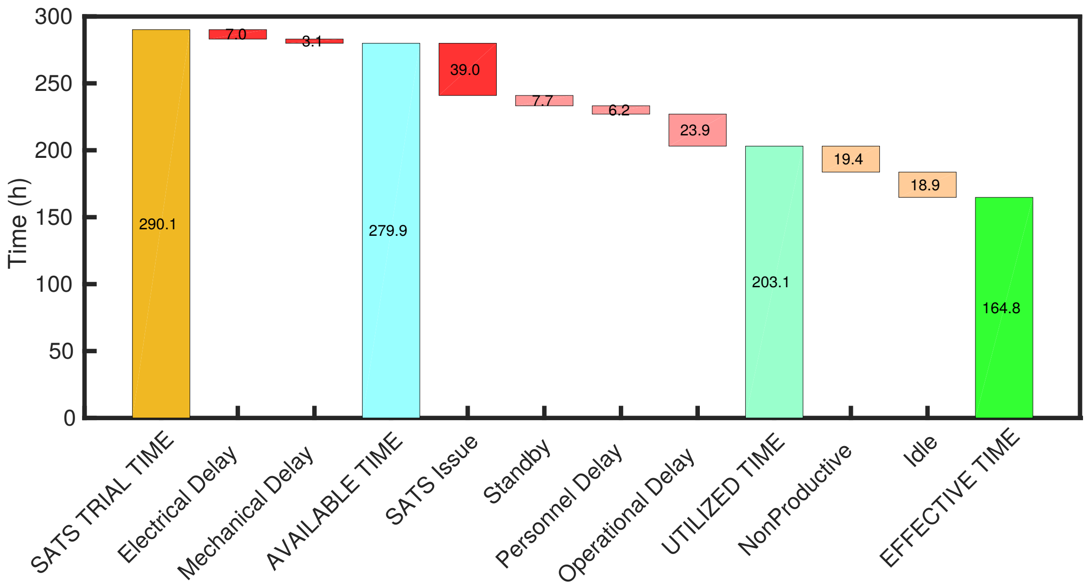


Figure 4.20: SATS trial time breakdown.

Table 4.8 gives a summary of the production time comparison. The additional delays seen in SATS operation resulted in an effective utilization which was 11.9% lower than manual operation.

Table 4.8: Summary of trial time breakdown.

	Manual	**SATS**	**Difference**
Total time spent in trial (h)	277.3	290.1	12.8h
Availability (%)	99.1	96.4	-3.7%
Utilized Availability (%)	79.8	72.5	-7.3%
Effective Availability (%)	**70.8**	**58.8**	**-11.9%**

Where:

Availability = Available Time / Trial Time

Utilized Availability = Utilized Time / Available Time

Effective Availability = Effective time / Available Time

Analysis of lost effective time

The analysis of utilization patterns has shown that SATS spent less time effectively working as a percentage of available time than manual operation. This was primarily due to issues with the automation system, and through sitting idle in the work area. These losses were slightly offset by less operational delays and personnel delays than manual operation. Further analysis has been undertaken into these key issues.

Issues with the autonomous system

A SATS issue is defined as any physical or software fault which prevents the bulldozer from operating under semi-autonomous command, but would not present an issue if under manual command. This essentially captures the reliability of the additional harware and software required for SATS to operate.

It was observed that issues with the SATS system contributed to a total of 39 hours of delay time throughout the trial, or 15 % of available time. Figure 4.21 provides a breakdown of the lost time due to SATS issues. The majority of delay time due to a SATS issue was caused by communications outages and pose solution errors.

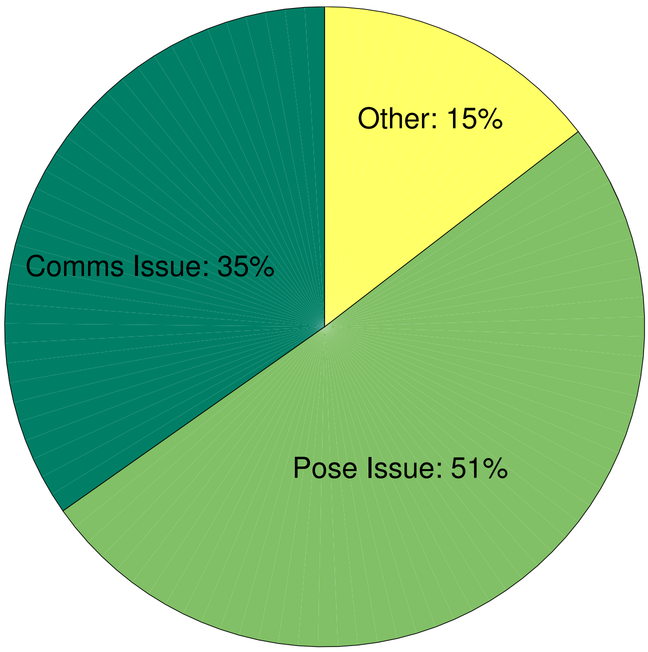


Figure 4.21: Pie chart of issues contributing to SATS Issue Time. The total time represented within in this pie chart is the 39 hours of SATS Issue time.

The system is commanded to pause work whenever a loss of communications or pose solution is detected, remaining stationary in the work area until service is restored. A communications outage is caused by a disruption to the transmission of information between the control station and the tractor over a 2.4 GHz data link. A pose solution outage is caused by a disruption of either; (i) GNSS-RTK correction information transmitted over the 2.4GHz data link from the local RTK base station; (ii) failure of the GNSS recievers on board the machine to find an accurate solution due to reduced view of the sky; or (iii) a communication issue on board the machine preventing timely distribution of the rtk or gnss information to the various machine subsystems. The portion of time marked as 'Other' includes time in which the machine did not work due to a range of issues, primarily physical faults with sensors and electronics connectors which required field maintenance.

Figure 4.22 shows a distribution of durations of each individual instance of Communications Issue and Pose Issue delays. The majority of time lost to SATS issues was accumulated within individual instances lasting 20 seconds or less. These intermittent faults were spread over the entire trial.

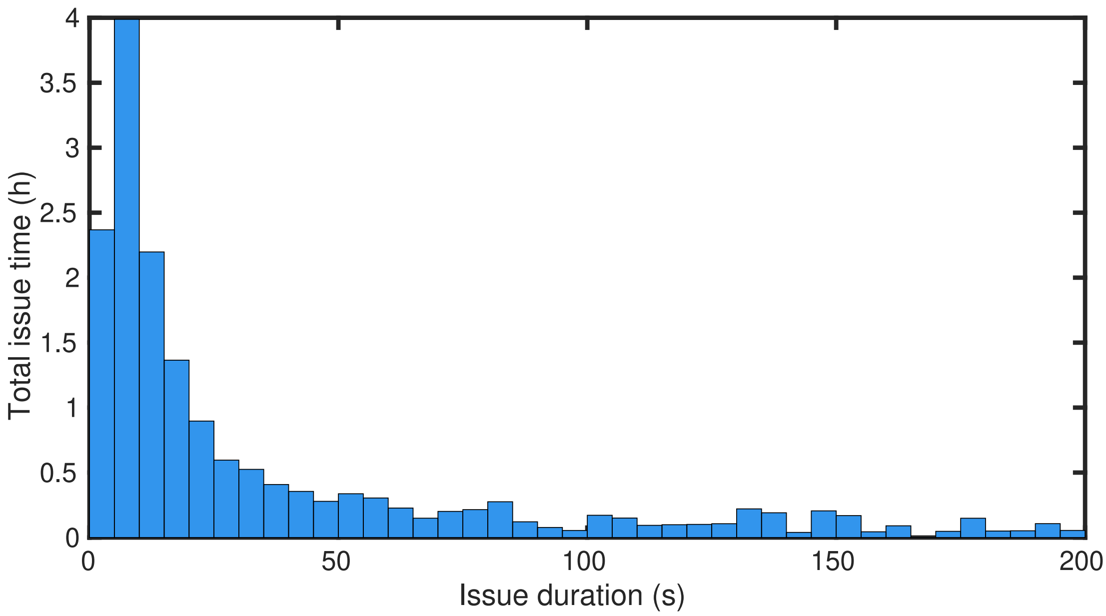


Figure 4.22: Distribution of the duration of SATS issues.

A significant portion of the SATS Issue time observed during the trial was due to outages of the 2.4 GHz data link. The wireless radio on board Bulldozer 2010 was impacted by rough vibration within the bulldozer, leading to intermittent disruptions in its ability to send and receive data. This issue was identified during the trial, however a more rugged replacement unit was only installed after the trial had finished due to delays in procurement. It is expected that the wireless communication will be more reliable in future tests of this machine.

Several improvements have been made to the positioning system following the completion of the trial of December 2016; (i) improved site communication infrastructure and on-board netowrk radio have improved the reliability of RTK corrections being recieed by the on-board GNSS recievers; and (ii) a bandwidth overload issue in the on-board system was identified to sporadically prevent the timely delivery of positioning information to the planning computer, resulting in a Pose issue to be reported. This has been remedied. No data is present to measure the improvement derived from these improvements, however it is estimated that a proportion of the time previously lost to pose issues has been recovered.

Operational and personnel delays:
Operational Delay time is accumulated during the inter-shift and mid-shift breaks which have a minimum frequency and duration mandated in the operator's terms of employment. When under manual operation, time is spent in transit between the work area and the break room, which is in addition to the minimum break time requirement. Operators of the semi-autonomous machine were able to reduce the amount of time lost to each break, as they were able to pause operation to take their breaks while the machine was still located within the work area.

Personnel Delay time is accumulated during un-planned personal breaks (e.g. bathroom) and when communicating with nearby personnel via radio. Operators of the semi-autonomous machine were also able to reduce the time lost to these delays, as the machine was able to continue production whilst the operator was otherwise occupied.

Consequently, it was observed that SATS accumulated a lower portion of its time in the categories of Operational Delay and Personnel Delay than was seen under manual operation. This result is interesting, as it suggests that the system is able to increase the portion of the operator's time that is spent actively utilizing a machine. It is expected that the portion of Operational Delay and Personnel Delay time will be reduced further as the operators become more skilled at assigning work to machines ahead of time.

Idle Time:
Idle time is defined as time spent with the machine stationary while located within in the work area, but is otherwise fit for work.

Figure 4.23 shows a breakdown of idle time over the course of the trial while in SATS mode. We see that 26% of this time was spent waiting for the operator's instructions and 10% was due to a cycle execution requiring operator assistance. The portion idle time listed as a 'Normal Transition' is due to the operator deliberately commanding the machine to pause work while planning the next sequence of moves.

Much of the idle time observed during the trial was accumulated in instances where the operator briefly paused work to assign another task to the machine. This should not be necessary, as the system is capable of accepting an updated mission while it completes its current assignment.

The idle time is attributed largely to operator inexperience. At the time of execution of this trial, most operators had accumulated less than 10 hours of experience operating the system. This trial therefore captures the state of the system in its initial stages of adoption. It is expected that with further operator training, the time spent idle due to these preventable causes will be reduced.

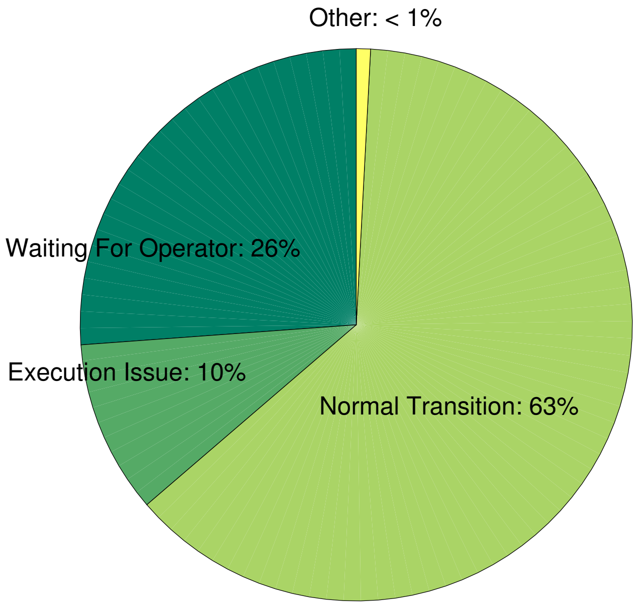


Figure 4.23: Breakdown of issues contributing to SATS Idle Time. The total time represented is the 18.9 hours of SATS Idle time.

Summary

This chapter has explored the effectiveness of the Caterpillar semi-autonomous tractor system by comparison against manual operation. Effectiveness was quantified as (i) the rate of material moved to prime per hour of effective time and (ii) the amount of time spent effectively working as a percentage of available time. The two modes of operation were compared by monitoring all work completed by a single D11T bulldozer which alternated working under manual and semi-autonomous command.

Productivity was measured in two zones designated within a production strip at Wilpinjong colliery, the first assigned to manual operation and the second assigned to SATS operation. The productivity of each zone was compared against a reference obtained using the pivot push simulation framework. It was found that in the manual zone, measurement was well aligned with simulation, and that in the SATS zone, measurement was approximately 15% less productive than simulation.

Effective availability was measured throughout the entire trial, primarily by monitoring the equipment status obtained from the Leica JDozer fleet monitoring system. The breakdown of effective time and delay time was accumulated individually for manual and SATS operation.

We draw the following conclusions:

- SATS is subject to more delays reducing effective time than manual operation.
- SATS is less productive than manual operation when effectively working.
- Many of the causes of this lost effectiveness have been traced to fix-able issues and reflect the maturity of this recently introduced technology. The issues have been targeted for improvement.

CHAPTER 5

Conclusions

Playing in the dirt
with a big yellow tractor
presents challenges

Overview and contributions

This thesis has studied the productivity of pivot push bulldozing to fill knowledge gaps required for continued improvement of the Caterpillar semi-autonomous tractor system (SATS). The haiku that prefaces this chapter speaks to the current state of SATS as a technology which is still in its early stages of development.

The motivation behind this thesis was a need to understand the productivity of a pivot push operation for two reasons: (i) to determine which of several variants of pivot push bulldozing should be preferred for implementation in the autonomous system; and (ii) to measure how the operation of SATS influences the effectiveness of the operation and identify how this can be improved.

It was determined that the productivity of pivot push would be best understood using simulation. This is because of the large number of uncontrolled variables which would influence the results of a direct experimental comparison. A fit-for-purpose pivot push simulation framework was developed concurrently work the work of this thesis. The simulation framework is able to generate a representative sequence of bulldozer actions which are required to move all material from the initial terrain geometry to the desired design geometry.

This thesis has presented an experimental validation of the pivot push simulation framework. The simulation framework was validated by comparison against data obtained during an experimental trial. The trial was carried out in a production strip at Wilpinjong colliery, in which the three methods were tested within separate designated zones. It was found that the simulation framework can reliably predict the productivity of pivot push subject to strip geometry and the chosen pivot push method. These findings were considered to validate the productivity predictions of the simulation framework.

This thesis has applied the pivot push simulation framework to determine the most productive pivot push method over a range of strip geometries. The simulations took place within a simulated environment based on the geometry of strips at Wilpinjong colliery. Five zones were used, each 36 m long, and subject to different strip geometry. The three selected methods were simulated within each of the five zones. It was found that Method 2 was marginally more productive than Method 3, and that both were significantly more productive than Method 1.

This information, in concert with other considerations around material compaction led to the selection of Method 3 to be implemented within the semi-autonomous system.

This thesis has bench marked the effectiveness of the semi-autonomous implementation of Method 3 through an experimental trial. The effectiveness of SATS was considered in two parts: (i) the productivity of the machine while effectively working within the strip; and (ii) the time spent in effective work as a percentage of available time. A strip at Wilpinjong colliery had two zones designated within it, the first dedicated to manual operation (which was used as a control for the trial) and the second dedicated to semi-autonomous operation. Productivity was measured whenever the bulldozer was located within one of the designated zones. Productivity of each mode of operation was compared against the productivity which was predicted for that zone by the simulation framework. Time in effective effort was measured whenever the bulldozer was located within the trial strip under trial conditions.

It was found that the productivity measured in the manual zone was well matched to the productivity prediction for the manual zone, but that the measured productivity in the SATS zone was approximately 15% lower than the prediction for the SATS zone. It was also found that the time spent in effective effort was lower for SATS than for manual operation. Analyses were undertaken which have identified the primary reasons for the lower effectiveness of SATS compared to what was expected for a manually-operated machine. Aspects of the operation which were identified to contribute most heavily to the lower-than-expected effectiveness are now able to be targeted for further improvement.

This is considered to fulfill the thesis aims which were to:

- validate a simulation framework for predicting the productivity of pivot push;
- use the validated simulation framework to identify how pivot push is most productively exe-

cuted; and

- evaluate the performance of semi-automated pivot push bulldozing using the simulation framework to compare actual performance to expected performance.

Future work

The conclusion of this thesis occurs amidst an ongoing project. As such, there are many avenues for work which continues from what has been presented here.

Simulation framework

Chapter 2 identified that the simulation framework reliably predicts productivity, but does so without predicting the micro-scale actions of the bulldozer. Accurate micro-scale predictions would enable a deeper analysis than was possible in this thesis. Ongoing work to refine the models underlying the simulation framework includes aspects such as velocity of travel, volume moved per cycle, distance travelled per cycle, and fuel consumed per cycle. The distributions of reversing velocity will be improved by replicating the logic which controls the selection of reverse gear under measured operation. The effect of grade of travel must also be considered in the velocity prediction. The distributions of volume moved to prime per cycle will be modified by further tuning of the pushable blade volumes model component of the simulation framework.

The analyses presented in this thesis have considered time spent as the only cost metric for productivity measurement. Alternative metrics of cost include fuel burned and distance travelled and these were both measured in the experimental trials. Further work seeks to extend the functionality of the simulation framework to accurately predict the fuel burn per cycle and distance travelled per cycle.

Further work must be undertaken to identify the point at which the per-volume cost of pivot push exceeds that of other methods such as an excavator filling trucks. This will require an economic model of bulldozer operation to be developed such that the cost (in dollars) per cycle can be predicted.

The results of this thesis have been drawn only from experiments on a single mine. Although the geometry and material conditions of this mine are considered representative, further validation could be carried out at other mines with different geometry.

Improvement of SATS

Chapter 5 identified several aspects of the SATS operation in which it was less efficient than an equivalent manual operation. Ongoing work between the University of Queensland and Caterpillar seeks to close these productivity gaps so that the autonomous system might eventually achieve a productivity which is equivalent to or greater than what is currently seen under manual operation.

Several productivity losses were identified to be caused by control logic of SATS, including the selection of reversing gear and the extra distance travelled per cycle. It is anticipated that the logic surrounding these aspects of the operation will be revised in upcoming system software updates.

Each operator had accumulated less than 10 hours of experience with the semi-autonomous system before the commencement of the trial presented in Chapter 4. As such there were some losses in effectiveness which arose due to inexperience, specifically a greater than expected amount of time spent idle within the work area and a greater than expected amount of time spent in unproductive cycles. Further training will focus on these issues so that operators gain a greater proficiency in commanding the system to operate efficiently.

Bibliography

Baitch, T. (2015). Mining Engineer, Anglo American, personal communication.

Berkhimer, E. (2011). *Selection and Sizing of excavating, loading, and hauling equipment*. Society for Mining, Metallurgy, and Exploration, Inc.

Bettens, S. (2016). Predicting pushable and optimal blade volumes for bulldozing. B.e. thesis, The University of Queensland - School of Mechanical & Mining Engineering.

Brundrett, S. (2014). Industry analysis of autonomous mine haul truck commercialization. M.b.a. thesis, Simon Fraser University.

Caterpillar (2001). *A Reference Guide to Mining Machine Applications*.

Caterpillar (2010). *SEBD0351-41 Caterpillar Track-Type Tractor Performance Handbook, Edition 41*.

Caterpillar (2012). *Caterpillar Command for Dozing product catalog*.

Caterpillar (2013). *Caterpillar Command for Hauling product catalog*.

Caterpillar (2016). *Caterpillar D11T product catalog*.

Chang, S.-K. (1983). *Languages For Automation*. Springer.

Cockburn, A. (2001). *Writing Effective Use Cases*. Addison-Weasley.

Cooke, T., Horberry, T., and Burgess-Limerick, R. (2012). Revisiting injury narratives to pinpoint human factor issues associated with surface mobile mining equipment. In *First international conference on Occupational Safety in Transport, Gold Coast, Queensland, Australia*, volume 2021.

Davidson, J., Collins, E., and McKibben, E. (1935). Tractive efficiency of the farm tractor. Technical report, Iowa state college of agriculture and mechanic arts.

Deloitte (2016). Tracking the trends 2016: The top 10 issues mining companies will face in the coming year. Technical report, Deloitte.

DJI (2016). *Phantom 4 user manual*.

Dudley, J. (2014). Enhancing awareness to support teleoperation of a bulldozer. Master's thesis, The University of Queensland - School of Mechanical & Mining Engineering.

Dyer, G. and Hill, K. (2011). Strip mining. In *SME Engineering Handbook*, chapter 10.8. Society for Mining, Metallurgy, and Exploration, Inc.

Garber, M. (1985). Tractive efficiency of a tracked vehicle. *Journal of Agricultural Engineering Research*, 32:359–368.

Grune, D., vanReeuwijk, K., Bal, H., Jacobs, C., and Langendoen, K. (2012). *Modern Compiler Design*. Springer, 2nd edition.

Hayes, T. G. (1997). Using dozers to remove coal overburden. *Mining Engineering*, 19 October 1997.

Hensel, R., Smith, Z., Austin, K., Choros, K., and McAree, P. (2017). Semi-autonomous tractor productivity under pivot push: methodology and productivity evaluation. Technical report, The University of Queensland - School of Mechanical & Mining Engineering.

Humphrey, J. D. and Wagner, J. D. (2011). Mechanical extraction, loading and hauling. In *SME Engineering Handbook*. Society for Mining, Metallurgy, and Exploration, Inc.

Klanfar, M., Kujundžić, T., and Vrkljan, D. (2014). Calculation analysis of bulldozer's productivity in gravitational transport on open pits. *Tehnički vjesnik/Technical Gazette*, 21:517–523.

Komatsu (2014). Autonomous haul system (ahs).

Langley, R. (1998). Rtk gps. *GPS World*, pages 70–76.

Leica-Geosystems (2013). *Leica Jigsaw JFleet Fleet Management System product catalog*.

Lucas, R. and Siddig Kizil, M. (2014). Optimisation of waste-dump lift heights for pre- strip operations. *Coal Operators' Conference*.

Lukacs, Z. (1998). Standard definitions for the benchmarking of availability and utilization of equipment. Technical report, Canadian Institute of Mining, Metallurgy, and Petroleum.

Macmillan, R. (2002). *The mechanics of tractor-implement performance: theory and worked examples: a textbook for students and engineers*.

Martin, J., Martin, T., Bennett, T., and Martin, K. (1982). *Surface Mining Equipment*. Martin Consultants.

MECMining (2015). Dozer Bulk Push Training Program Presentation, pp 1-73.

Medland, D. (2015). Principal, Medland Mining Services, personal communication.

Miyashita, K., Morioka, I., Tanabe, T., Iwata, H., and Takeda, S. (1992). Symptoms of construction workers exposed to whole body vibration and local vibration. *Occupational and Environmental Health*.

Nott, K. (2015). Mining Engineer, Peabody Energy Australia, personal communication.

Parker, S. P. (2003). *McGraw-Hill dictionary of scientific and technical terms*. McGraw-Hill.

Parreira, J. (2013). *An Interactive Simulation Model to Compare an Autonomous Haulage Truck System with a manually-Operated System*. PhD thesis, The University of British Columbia.

Pix4d (2015). *Pix4dMapper user manual*.

Pope, M., Magnusson, M., Lundstrom, R., Hulshof, C., Verbeek, J., and Bovenzi, M. (2002). Guidelines for whole-body vibration health surveillance. *Journal of Sound and Vibration*.

Shonts, E. and Nettleton, J. (2011). *Strip Mine Planning and Design*. Society for Mining, Metallurgy, and Exploration, Inc.

Sinclair, N. (2016). A cost benefit analysis model comparing dozer side-cutting and excavator side-casting techniques on the highwall in a dozer bulk push operation. B.E. Thesis, The University of Queensland - School of Mechanical & Mining Engineering.

Tsuji et al., T. (2011). 3-d dem simulation of cohesive soil-pushing behavior by bulldozer blade. *Journal of Terramechanics*.

Uren, Z. and Nehring, M. (2015). Development of dozer push optimisation software for commodore coal mine. *Journal of Research Project Review*, 4:59–65.

U.S. Army (2000). *Field Manual 5-434: Earthmoving Operations*. Washington, DC.

Xia, K. (2009). A framework for earthmoving blade/soil model development. *Journal of Terramechanics*.

APPENDIX A

Use Case Document

Contributions to Appendix A

Appendix A contains an ensemble of Use Cases [Cockburn, 2001] which describe pivot push in a greater level of detail than was presented in Chapter 1. The author was assisted by multiple other contributors in the creation of this document. The contributions of each contributor are expressed below.

Contributor	Statement of contribution
Richard Hensel (Candidate)	Conception and design (50%) Analysis and interpretation (50%) Drafting and editing (70%)
Tim Cullen	Conception and design (20%) Analysis and interpretation (20%) Drafting and editing (20%)
Ross McAree	Conception and design (30%) Analysis and interpretation (10%) Drafting and editing (5%)
David Medland	Analysis and interpretation (5%)
Matt Addley	Analysis and interpretation (10%)
Sean Mumford	Analysis and interpretation (5%)
Kevin Austin	Drafting and editing (5%)

THE UNIVERSITY OF QUEENSLAND
AUSTRALIA

Smart Machines Group

Bulldozer Pivot Push
Use Case Document

Version 4

Richard Hensel
Tim Cullen
Ross McAree
David Medland
Matt Addley
Sean Mumford
Kevin Austin

Table of Contents

P - Preamble

P 1 Document Purpose

This document describes the structure of pivot push bulldozing, a mining method used in opencut strips. Information is presented as an ensemble of Use Cases. The intent is to present information in a format aligned to the automation problem and with unfolding detail of the subtleties and variations. Each use case identifies its goals, the actors involved, the main success scenario and alternative scenarios associated with it.

P 2 Nomenclature and conventions

Notation:

- Use cases are identified in the text by camel-case bold e.g. **BulkDozerPush**
- Actors are identified in the text by camel-case italic, e.g. *DozerOperator*

Direction of Orientation:

- The high wall end of the strip is the **left side** in cross sectional images and the **back/rear** in slot dozing operations.
- The low wall end of the strip is the **right side** in cross sectional images and the **front** in slot dozing operations.

Convention:

- If a use case is called, it can be carried out only if the precondition is met.
- Conversely, if a use case is called and the precondition is not met, the use case cannot be carried out. In this case, proceed to next step.

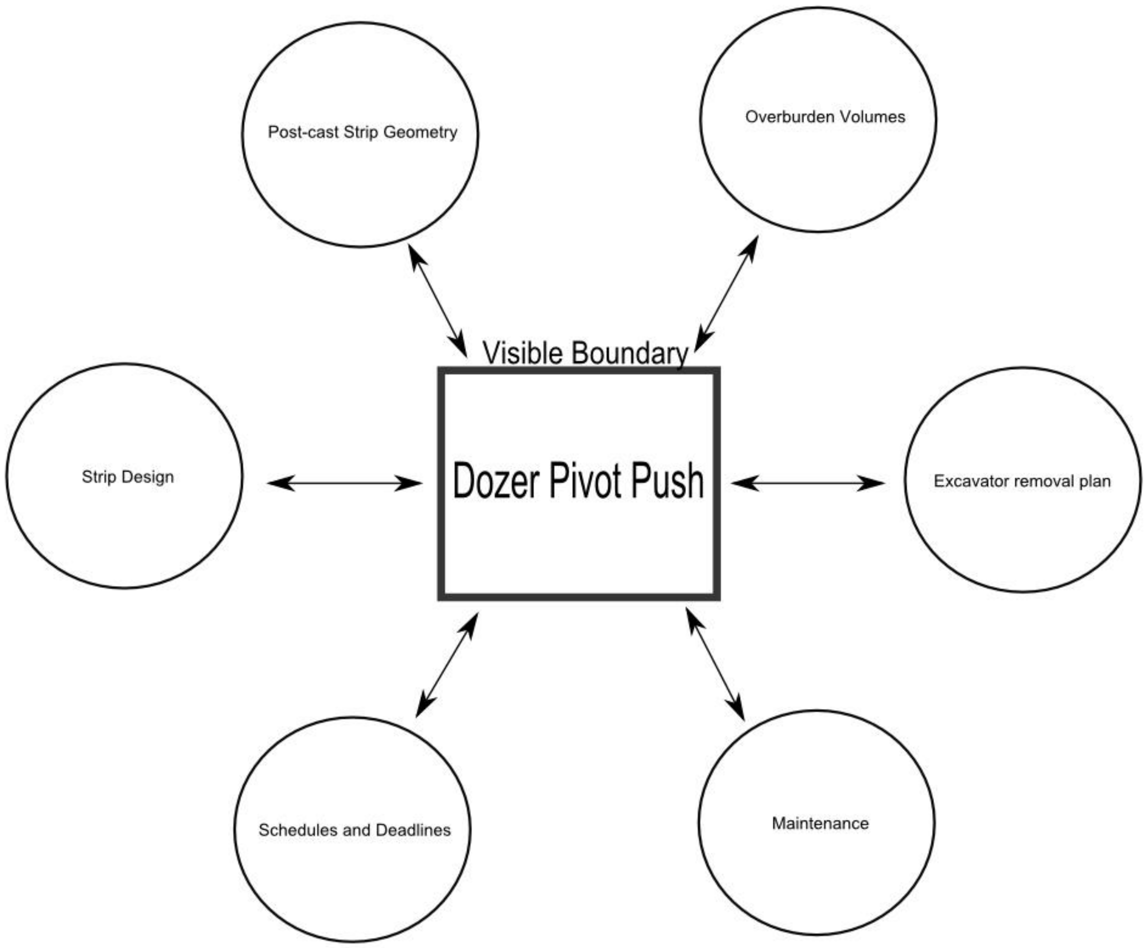
Abbreviations:

PGC: ProgressiveGradeCutting
CGC: ConstantGradeCutting
EWG: EstablishWorkingGrade
THD: TipHeadDownhill
THL: TipHeadLevel
THU: TipHeadUphill
BSD: BackStackDownhill
BSU: BackStackUphill

P 3 Cast of Characters

Actor	Role Description
BlastTeam	Responsible for planning and executing the overburden blast.
Dozer	Also known as a Track Type Tractor. Commanded by the *DozerOperator* and used for transforming the blasted overburden material to the target profile. Usually 5-6 dozers work simultaneously in a strip.
DozerOperator	*DozerOperator* works on board a Dozer and is responsible for commanding the *Dozer*. The *DozerOperator* works under the supervision of the *DozerPushSupervisor.*
DozerPushSupervisor	Supervises the dozer push process referencing the plan through the *DozerProductionSystem* and communicating intent to the *DozerOperator(s).*
HighwallExcavator	Works simultaneously to and in collaboration with the *Dozers.* Removes material from the highwall region so that it can be more easily pushed by the *Dozers.*
MineDesignEngineer	Responsible for designing the pivot push operation for each individual strip to achieve the lowest economic cost. Also determines the point where it becomes more economical to cease pivot push and remove the remaining overburden with an *OverburdenExcavator.*
OverburdenExcavator	Responsible for removing the overburden remaining above the top of coal after pivot push has ceased.
Surveyor	Is requested to complete surveys of the pit. Uses a UAV to survey the strip, and communicates the results as a 3D terrain map.

P 4 Visible Boundary



HL – High Level Use Cases

HL 1 StripMining

Traces To

DesignDozerPush
DozerPivotPush

Goal: To uncover and mine the coal from the current strip.

Brief Description: The *MineDesignEngineer* uses the survey information to design the dozer pivot push operation and communicates the plan to the *DozerPushSupervisor*. The *BlastTeam* plans and executes a blast of the overburden with the aim of fragmenting the material and casting as much to prime as possible. The *DozerPushSupervisor* orders commencement of the pivot push operations. Once the overburden has been moved and the coal exposed, the coal is removed.

Primary Actor: *DozerPushSupervisor.*

Secondary Actors: *MineDesignEngineer, Surveyor, DozerOperator, Dozer, HighwallExcavator.*

Precondition: Target working strip has been prepared for mining.

Main Success Scenario:

1. *The MineDesignEngineer* **DesignsDozerPush** based on an aerial survey of the pit in its pre-blast state.
2. The *BlastTeam* executes blasting of the strip in order to fragment and cast the overburden as far as practicable into the void.
3. The *DozerPushSupervisor* directs the *Dozers* and *HighwallExcavators* to complete **DozerPivotPush** until the end state identified in the Pivot Push design is achieved.
4. Mining commences.

HL 1.1 DesignDozerPush

Traces From

StripMining

Goal: To provide a design of the dozer push which will allow material to be moved following the most economic method.

Brief Description: The *MineDesignEngineer* uses survey information to formulate a design of the dozer push for each region of the pit. A Key component of this design is the selection of Pivot Point location. The Pivot Point is located at the intersection of the level of the top of coal and a 45 degree line inscribed from the bottom of the coal face. The design is formed to deliver maximum material movement through the most economic method. The volumes and cost calculations are performed iteratively until a feasible design solution is obtained. The design is (usually) compiled into an overall plan which also includes an aerial view of the site and notes regarding the dozer push operations. This plan is communicated to the *DozerPushSupervisor* and the *Dozers.*

Primary Actor: *MineDesignEngineer*

Secondary Actors: *DozerPushSupervisor, Dozers.*

Precondition: A survey has been taken of the strip.

1. The *MineDesignEngineer* sets the Target Cutting Profile to be level with the top of coal.
2. The *MineDesignEngineer* generates a Target Dumping Profile which would accomodate all material moved to achieve the Target Cutting Profile according to **TargetDumpingProfileGuidelines**.
3. The *MineDesignEngineer* uses a geometry-based productivity model to verifiy that this Target Dumping Profile can be most economically achieved by bulldozers instead of excavators.
4. The *MineDesignEngineer* creates a cross-section design which shows the Target Cutting Profile and Target Dumping Profile.
5. The *MineDesignEngineer* communicates the dozer push design to the *DozerPushSupervisor*.

Alternative Scenarios:

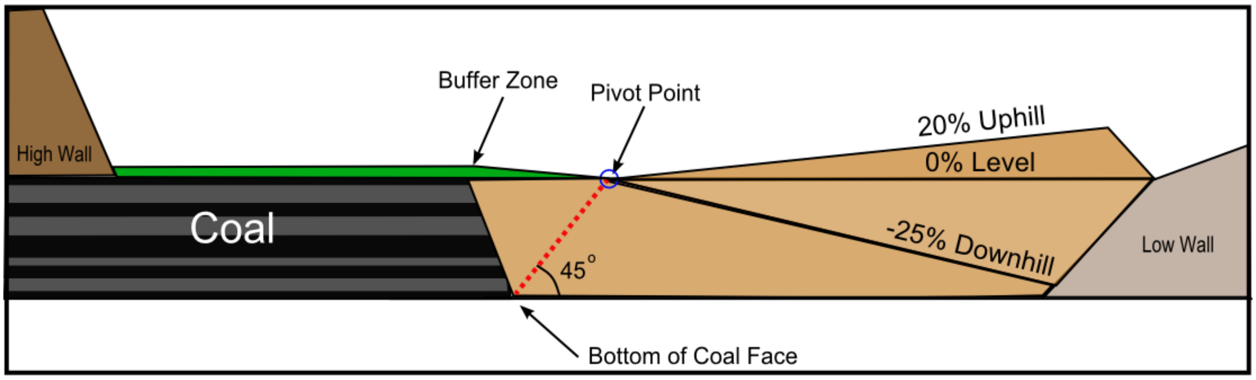
3a. The capacity of the target dumping region is insufficient to contain all overburden above the Target Cutting Profile. (See PlanPivotPush Figure 2).

3a.1. The *MineDesignEngineer* uses a geometry-based productivity model to estimate the cost of leaving a bench of overburden at one flitch depth (~3m) to be removed by the *HighwallExcavator.*
3a.2. The *MineDesignEngineer* uses a geometry-based productivity model to estimate the cost of pushing the additional overburden up a grade greater than 20%.
3a.3. The *MineDesignEngineer* uses a geometry-based productivity model to estimate the cost of placing the additional overburden at a further push distance than the previous low wall.
3a.4. The *MineDesignEngineer* updates the design to have the overburden removed using the most economical method.
3a.5. Return to step 3.

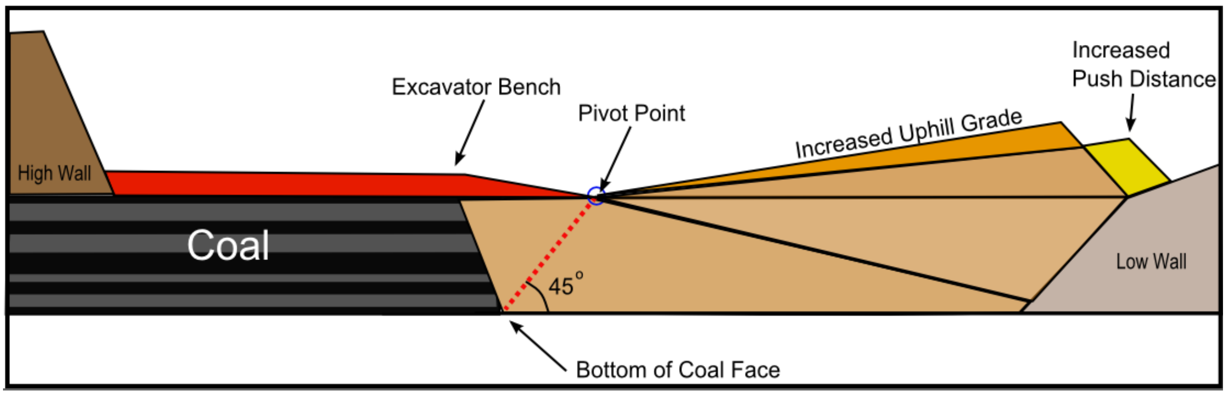
Supplementary Information:

TargetDumpingProfileGuidelines
The profile of the target dumping region is subject to the following constraints:

- Maximum uphill grade of dumping region is 20%.
- Maximum back stacking push distance is the top of the low wall of the previous strip.



DesignDozerPush Figure 1: Initial Plan.



DesignDozerPush Figure 2: Alternative Plans

HL 1.2 DozerPivotPush

Traces From

Traces To

PrepareWorkArea
EstablishworkingGrade
ProgressiveGradeCutting
TipHeadDownhill
BackStackDownhill
BackStackUphill
ClearTopOfCoal

Goal: Remove overburden from above the target coal seam following a permutation of the available operation tactics.

Brief Description: The *DozerPushSupervisor* inspects the blasted strip to identify any safety hazards before ordering the operation to commence. The work area is prepared by removing steep or rough sections and outlining the slots.

The *Dozer* **EstablishesWorkingGrade**, to extend a traversable grade to the Pivot Point, allowing access to the void for Prime Dumping.

While the void is not yet full to level, the *Dozer* removes overburden by following either **ProgressiveGradeCutting** or **ConstantGradeCutting,** while dumping into the void following either **TipHeadDownhill and BackStackDownhill** or **TipHeadLevel.**

Once the void is full to level the *Dozer* removes overburden following the same cutting tactic as in Epoch 2, while dumping above the void by either **BackStackUphill** or **TipHeadUphill.**

Four permutations of the cutting and dumping tactics are illustrated below.
Depending on the economic cost, the final overburden above coal is removed by either the *Dozer* or by the *OverburdenExcavator.*

Primary Actor: *Dozer*

Secondary Actors: *DozerPushSupervisor, HighwallExcavator, and OverburdenExcavator.*

Precondition: Overburden has been blasted and a design of the dozer push has been communicated to the *DozerPushSupervisor* and *Dozer.*

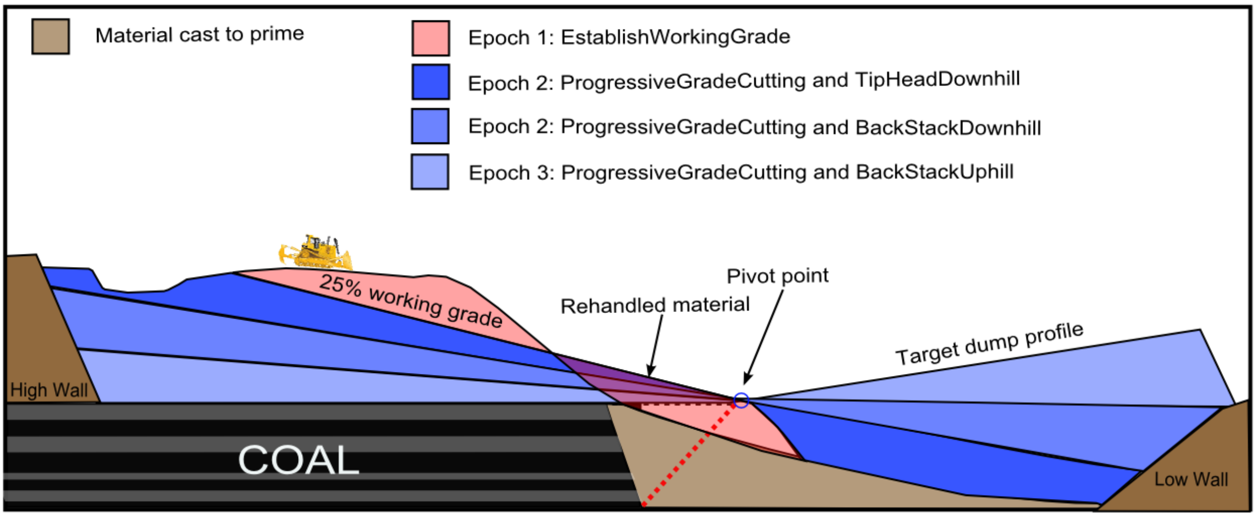
Main Success Scenario:

1. The *DozerPushSupervisor* examines the post-blast surface of the overburden and orders specific operations that are carried out by the *HighwallExcavator* and *Dozers* to **PrerareWorkingArea.**
2. The *Dozer* removes the steep crest at the edge of the cast profile to **EstablishWorkingGrade** and removes overburden at this grade until the working grade intersects the Pivot Point.
3. The *Dozer* removes overburden material by **ProgressiveGradeCutting** or **ConstantGradeCutting** while dumping via **TipHeadDownhill-and-BackStackDownhill** or via **TipHeadLevel** until the void is filled to level.
4. The *Dozer* removes overburden material by **ProgressiveGradeCutting** or **ConstantGradeCutting** while dumping via **BackStackUphill** or **TipHeadUphill** until the target cutting profile is reached.
5. The *Dozer* **ClearsTopOfCoal.**

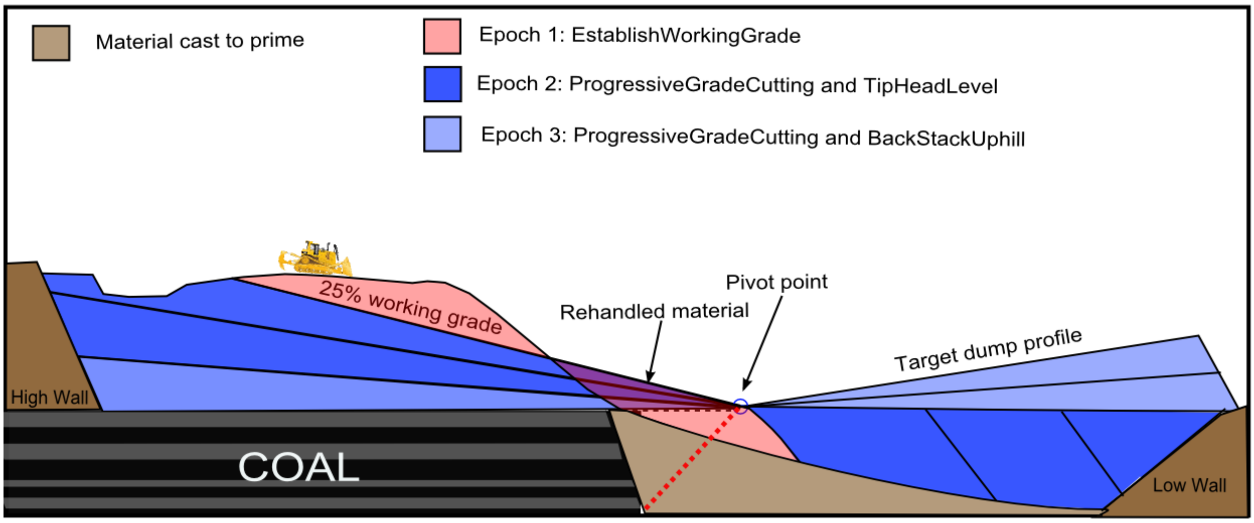
Alternatives:

5a. **The target cutting profile is offset from the top of coal, with the remainder to be removed by excavator.**

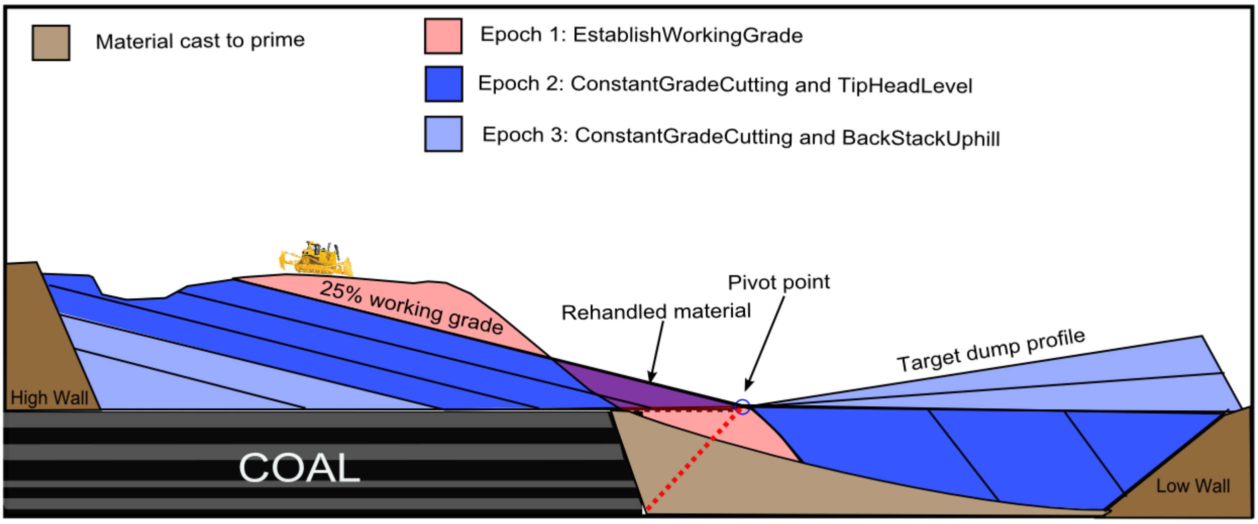
5a.1. The *OverburdenExcavator* removes the material remaining above the top of coal, filling into haul trucks to be taken from the pit.



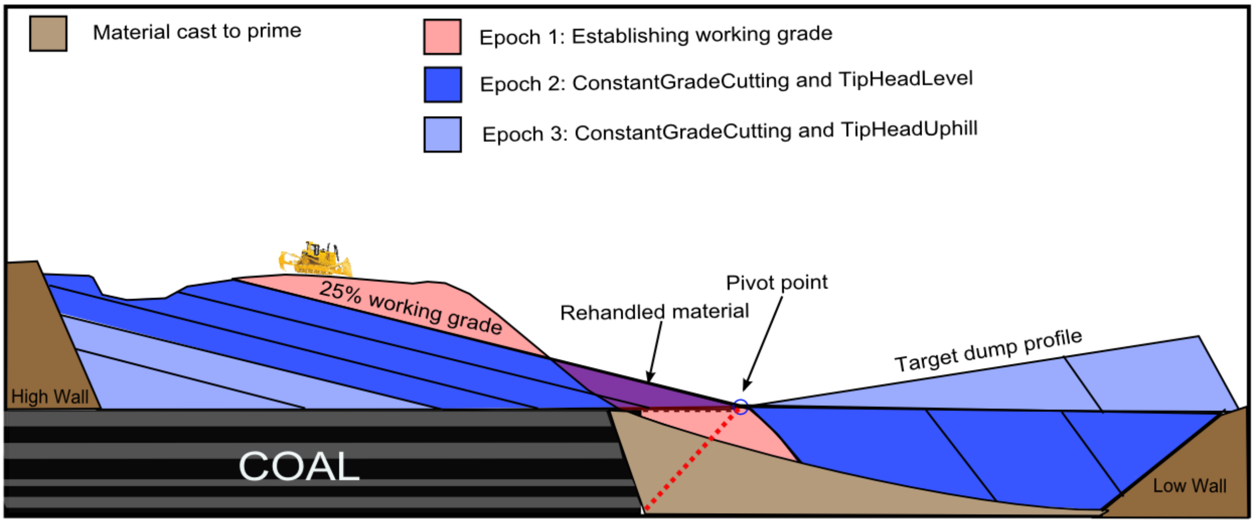
DozerPivotPush Figure 1.



DozerPivotPush Figure 2.



DoerPivotPush Figure 3.



DozerPivotPush Figure 4.

OL – Operational Level Use Cases

OL 1 PrepareWorkArea

Traces From

DozerPivotPush

Goal: To establish slots in the blasted strip and remove safety hazards.

Brief Description: The *DozerPushSupervisor* examines the post-blast topography and identifies potential safety hazards. If necessary, dozers are used to clear steep or rough sections of the blasted terrain. If necessary, a dozer is used to perform highwall pushover on sections of the crest which have not completely collapsed into the void. The *Dozer* outlines the slots along the length of the dozer push strip for slot dozing to begin.

Primary Actor: *Dozer*

Secondary Actors: *DozerPushSupervisor.*

Precondition: The overburden has been blasted.

Main Success Scenario:

1. The *DozerPushSupervisor* examines the power trough, high wall, and post-blast overburden surface to verify that the area is safe for dozer push to begin.
2. The *Dozer* enters the work area, and identifies rough terrain near the power trough of the blast profile which must be cleared before slot dozing may commence.
3. The *Dozer* performs grading pushes to clear rough or uneven sections so that the dozer may more easily traverse the terrain.
4. The *Dozer* establishes slots by **SlotDozing** from front to back along the top of the blast overburden profile. This begins at the front of the traversable area of overburden and continues until one slot depth of material has been removed from all slots in the dozer's work area.

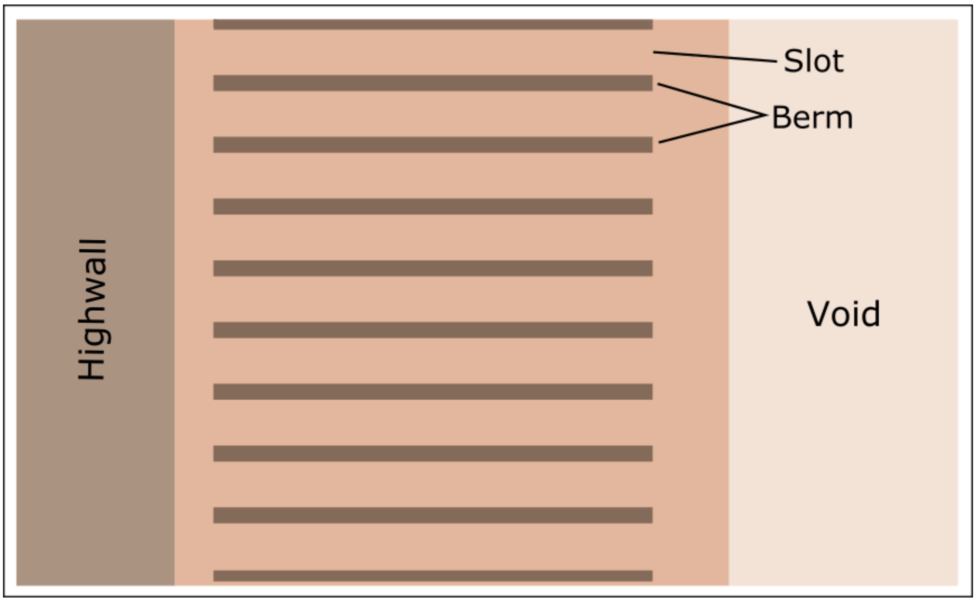
Alternatives:

1a. An uncollapsed section of the previous highwall remains after blasting, creating a steep crest at the void side of the overburden.

1b.1. The *DozerOperator* consults the *DozerPushSupervisor* to gain safety approval to perform a steep highwall pushover.
1b.2. The *Dozer* removes the topmost corner of the steep crest, pushing it into the void and removing the risk of wall collapse.
1b.2. Return to Step 1.

2b. Floor of power trough is too low to allow *HighwallExcavator* to reach the top of the high wall.

2b.1. A *Dozer* constructs a raised bench at the highwall to allow the highwall excavator to reach the entire wall for cleaning.
2b.2. Return to Step 1.



PrepareWorkArea Figure 3: Outline slots

OL 2 EstablishWorkingGrade

Traces From

DozerPivotPush

Traces To

TipHeadDownhill
SlotDozing

Goal: To establish a working grade (20% - 30%) on the overburden that extends from the highwall exccavator bench to the pivot point, allowing prime production to begin.

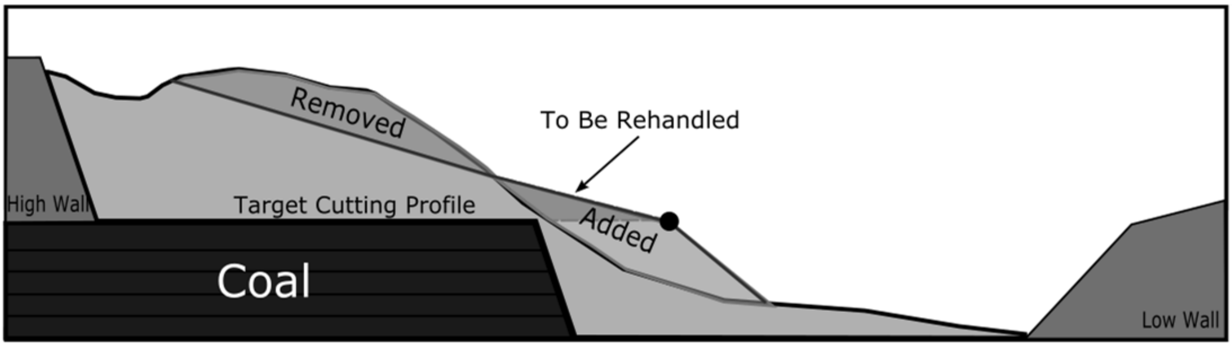
Brief Description: The *Dozer* establishes a working grade by **SlotDozing** while dumping via **TipHeadDownhill.** The operation is continued until the grade extends along the top surface of the overburden to the pivot point. Material cannot yet be dumped in to prime as the gradient is too steep for the dozer to gain access to the void. Re-handle is inherent in this process and some material may be re-handled several times until the Pivot Point is reached. The grade may be controlled between a range of 25% +- 5% to ensure that grade intersects with the Pivot Point. The process is illustrated in EstablishWorkingGrade Figure 1.

Primary Actor: *Dozer*

Precondition: The workable surface of the overburden is at a grade greater than 30% and the work area has been prepared by establishing slots.

Main Success Scenario:

1. The *Dozer* performs **SlotDozing,** from the front to the back of the existing slots, dumping by **TipHeadDownhill** to extend the end of the slot at a grade of 25% +- 5% downhill.
2. The *DozerOperator* identifies whether the current grade will intersect with the Pivot Point.
3. The *Dozer* modifies the grade for subsequent tip heading to cause an intersect with the Pivot Point.
4. Repeat 1-3 until the working grade intersects with the Pivot Point.



EstablishWorkingGrade Figure 1: Establish Working Grade.

OL 3 ProgressiveGradeCutting

Traces From

DozerPivotPush

Traces To

SlotDozing
CleanHighwallWithExcavator

Goal: To remove all overburden down to the target cutting profile above the top of coal, gradually reducing the grade about the pivot point.

Brief Description: The dozer push design specifies a target cutting profile, above which all material is to be removed. This material is removed by **slot dozing**, wherein the top surface of the overburden is kept as closely as possible to approximate a straight line. The grade of the top surface is gradually reduced from the initial working grade to horizontal by removing more material from the back than the front of the slot. The location for beginning each individual cut is determined by the deviation from the desired grade at that location. The dozer leaves a 12 metre wide bench at the rear of the slot to be periodically cleared by the *HighwallExcavator.* The process is illustrated in ProgressiveGradeCutting Figure 1.

Primary Actor: *Dozer.*

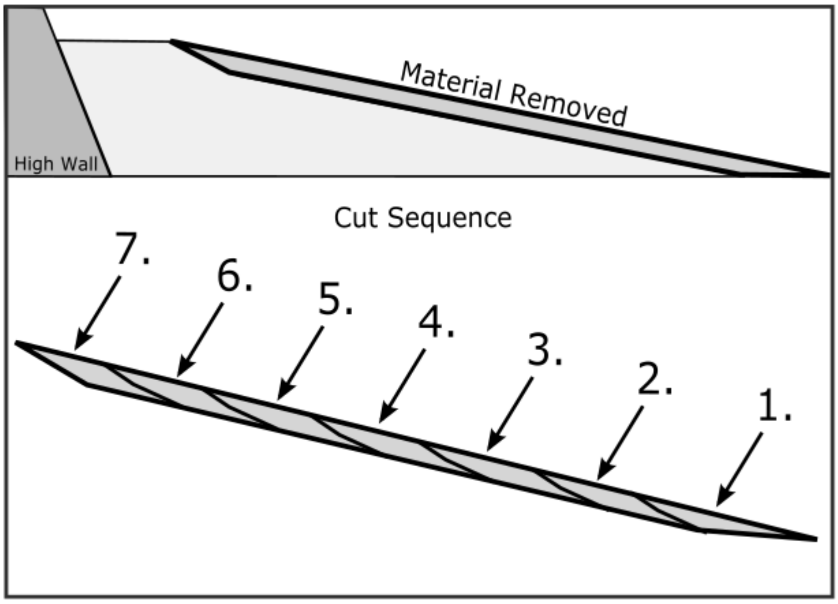
Secondary Actors: *HighwallExcavator*

Precondition: A working grade has been established and material exists above the target cutting profile.

Main Success Scenario:

1. The *Dozer* performs **SlotDozing** from the front to the back of the dozing region, until the slot berms have reached a height of one dozer blade. Cuts are sequenced to remove more material from the back thn the front, reducing the grade of the overburden at a constant rate.
2. Repeat 1 until the floor of the slot is below the height of the excavator bench.
3. The *HighwallExcavator* completes **CleanHighwallWithExcavator** to remove material from the highwall and excavator bench at a depth of 1 excavator flitch.
4. The *Dozer* **ClearsExcavatorSpoilPile.**

5. Repeat steps 1-4 until the overburden material has been removed down to the target cutting profile.

Alternatives: 

ProgressiveGradeCutting Figure 1.

OL 4 ConstantGradeCutting

Traces From

DozerPivotPush

Traces To

SlotDozing
CleanHighwallWithExcavator

Goal: To remove overburden down to thetarget cutting profile specified by the Dozer Push design.

Brief Description: The dozer push design specifies a target cutting profile, above which all material is to be removed. This material is removed by slot dozing, wherein the top surface of the overburden is kept as closely as possible to approximate a straight line. The grade of the top surface is maintained by removing equal amounts of material from the front and rear of the slot. The constant grade intersects with a horizontal level once the operation has progressed. The location for beginning each individual cut is determined by the deviation from the desired grade at that location. The dozer leaves a 12 metre wide bench at the rear of the slot to be periodically cleared by the *HighwallExcavator.* The process is illustrated in ConstantGradeCutting Figure 1.

Primary Actor: *DozerOperator*.

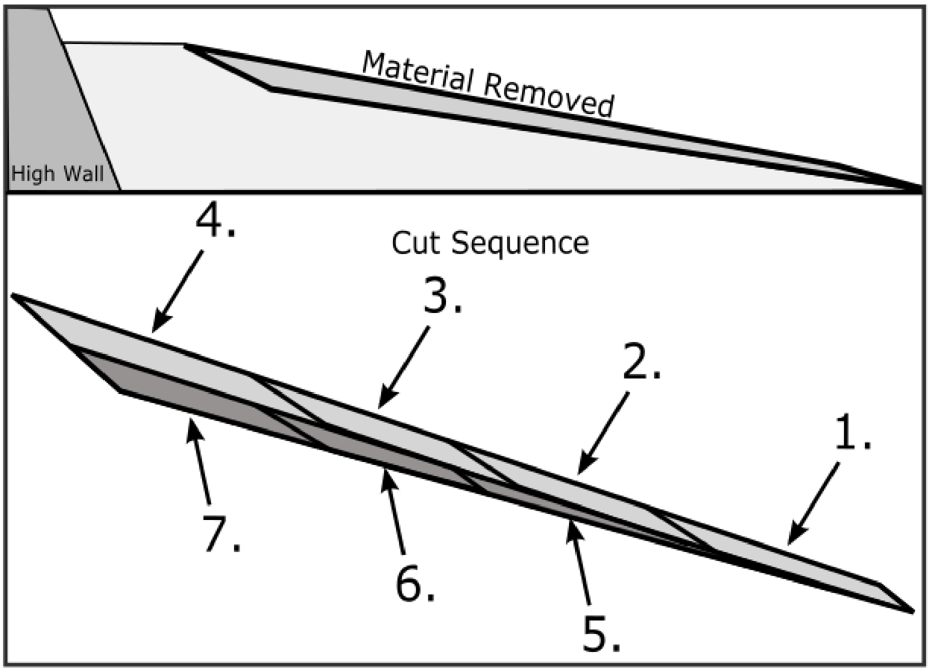
Secondary Actors: *HighwallExcavator*

Precondition: A working grade has been established and material exists above the target cutting profile.

Main Success Scenario:

1. The *Dozer* performs **SlotDozing** from the front to the back of the dozing region, until the slot berms have reached a height of one dozer blade. Cuts are sequenced to remove material uniformly along the length of the slot so that a constant grade is maintained.
2. Repeat 1 until the floor of the slot is below the height of the excavator bench.
3. The *HighwallExcavator* completes **CleanHighwallWithExcavator** to remove material from the highwall and excavator bench at a depth of 1 excavator flitch.
4. The *Dozer* **ClearsExcavatorSpoilPile.**
5. Repeat steps 1-4 until the overburden material has been removed down to the target cutting

profile.



ConstantGradeCutting Figure 1.

OL 5 TipHeadDownhill

Traces From

DozerPivotPush

Traces To

TipHeadSafely

Goal: To extend a downhill dump profile extending into the void.

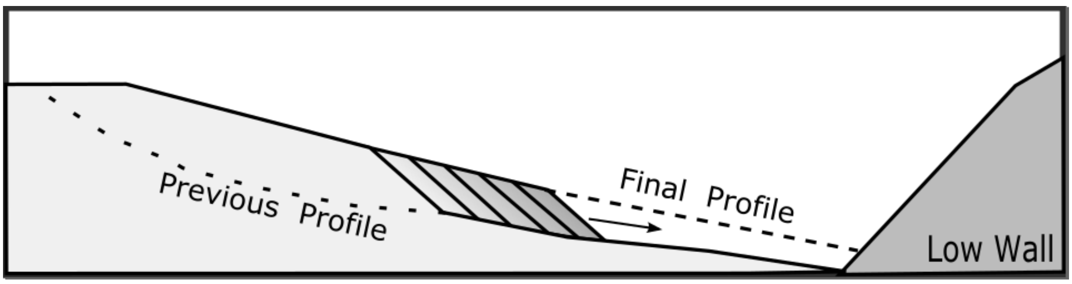
Brief Description: The *Dozer* dumps material from successive slot dozing cycles using the tip head method to achieve the desired downhill grade (-20 to -30%). The Process is illustrated in TipHeadDownhill figure 1.

Primary Actor: *Dozer.*

Secondary Actors: None.

Main Success Scenario:

1. The *DozerOperator* employs **TipHeadingSafely** to extend a tip heading profile at the desired grade from the end of the slot (TipHeadDownhill Figure 2).
2. The DozerOperator compares the resultant grade at the end of the tip head to the desired grade.
3. The *Dozer* employs **TipHeadingSafely** to dump a load the end of the tip head region, correcting any deviation from the desired grade.
4. Repeat 1 until the downhill tip head profile reaches the target point.



TipHeadDownhill Figure 1: TipHeadDownhill

OL 6 TipHeadLevel

Traces From

DozerPivotPush

Traces To

TipHeadSafely

Goal: To extend a level dump profile extending into the void.

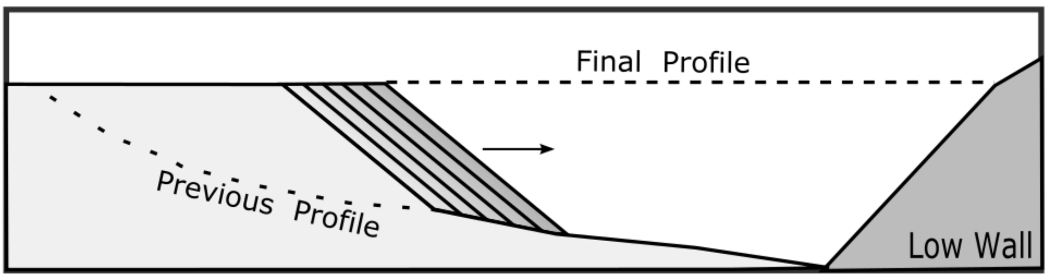
Brief Description: The *Dozer* dumps material from successive slot dozing cycles using the tip head method to achieve the desired level grade (0%). The Process is illustrated in TipHeadLevel Figure 1.

Primary Actor: *Dozer.*

Secondary Actors: None.

Main Success Scenario:

1. The *DozerOperator* employs **TipHeadingSafely** to extend a tip heading profile at the desired grade from the end of the slot.
2. The DozerOperator compares the resultant grade at the end of the tip head to the desired grade.
3. The *Dozer* employs **TipHeadingSafely** to dump a load the end of the tip head region, correcting any deviation from the desired grade.
4. Repeat 1 until the downhill tip head profile reaches the target point.



TipHeadLevel Figure 1: Tip Heading to Level

OL 7 TipHeadUphill
Version: 9.0
Created on 3/8/2017

Traces From

DozerPivotPush

Traces To

TipHeadingSafely

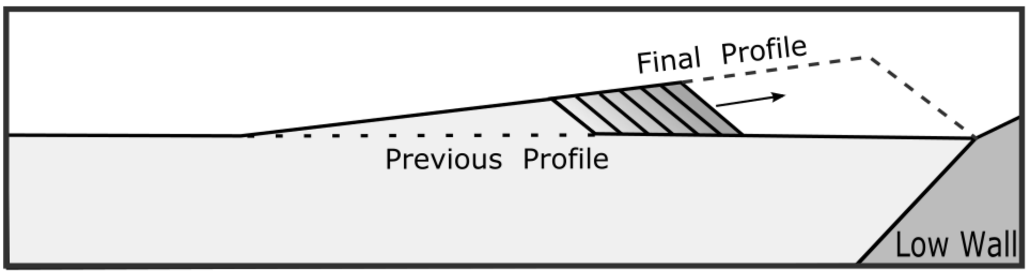
Goal: To extend an uphill dump profile above the void.

Brief Description: The *Dozer* dumps material from successive slot dozing cycles using the tip head method to achieve the desired grade. (10-20%). The process is illustrated in TipHeadUphill Figure 1.

Primary Actor: *Dozer.*

Secondary Actors: None.

Main Success Scenario:
1. The *DozerOperator* employs **TipHeadingSafely** to extend a tip heading profile at the desired grade from the end of the slot.
2. The DozerOperator compares the resultant grade at the end of the tip head to the desired grade.
3. The Dozer employs TipHeadingSafely to dump a load the end of the tip head region, correcting any deviation from the desired grade.
4. Repeat 1 until the downhill tip head profile reaches the target point.



TipHeadUphill Figure 1: Tip Heading Uphill

OL 8 BackStackingDownhill

Traces From

DozerPivotPush

Traces To

ChangeSlots

Goal: To place overburden material into the void until the void is filled to a level profile.

Brief Description: Loads of overburden material are stacked into the void in a structured manner to gradually raise the grade of the dumping profile to level. The grade is raised by creating a series of wedges. each wedge is created as a series of lifts. Lifts are created by stacking and flattening. The process is illustrated in BackStackDownhill Figure 1.

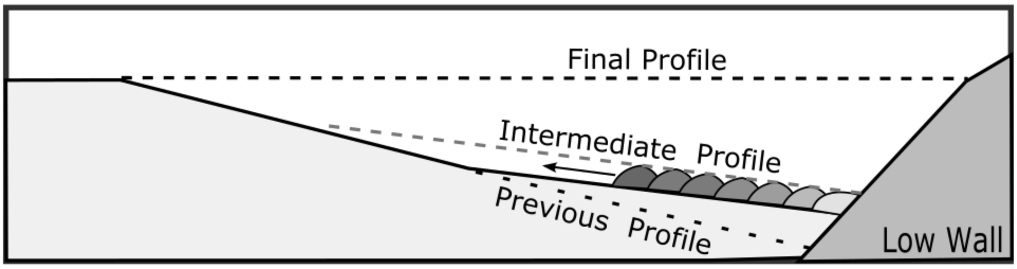
Primary Actor: *Dozer*

Secondary Actors: None.

Precondition: A downhill profile has been created in the void by **TipHeadingDownhill** to the low wall toe.

Main Success Scenario:

1. The *Dozer* begins a new lift by **Stacking,** beginning at the low wall, with a length of approximately three stacks.
2. The *Dozer* **Flattens** the previously created lift until a new load can be pushed along the top of the previous lift without spilling from the edges of the blade.
3. The Dozer **ChangesSlots** to work in another slot which has not yet been backstacked.
4. Repeat 1-3 until all slots being worked by the dozer have been backstacked to the same level.
5. The *Dozer* begins a new lift by **Stacking,** beginning at the low wall, with a length extending to approximately two stacks beyond the end of the previous lift.
6. The *Dozer* **Flattens** the previously created lift until a new load can be pushed along the top of the previous lift without spilling from the edges of the blade.
7. The Dozer **ChangesSlots** to work in another slot which has not yet been backstacked.
8. Repeat 1-3 until all slots being worked have been filled to level.



BackStackDownhill Figure 1: Backstacking Downhill.

OL 9 BackStackingUphill

Traces From

DozerPivotPush

Traces To

ChangeSlots

Goal: To stack material uphill from a level dump profile above the filled void.

Brief Description: Loads of overburden material are stacked into the void in a structured manner to gradually raise the grade of the dumping profile from level. The grade is raised by creating a series of wedges. each wedge is created as a series of lifts. Lifts are created by stacking and flattening. The operation is complete when all overvurden material has been removed or when the the grade of the uphill profile has ben rasised to 20% - the economic limit for backstacking. The process is illustrated in BackStackUphill Figure 1.

Primary Actor: *Dozer*

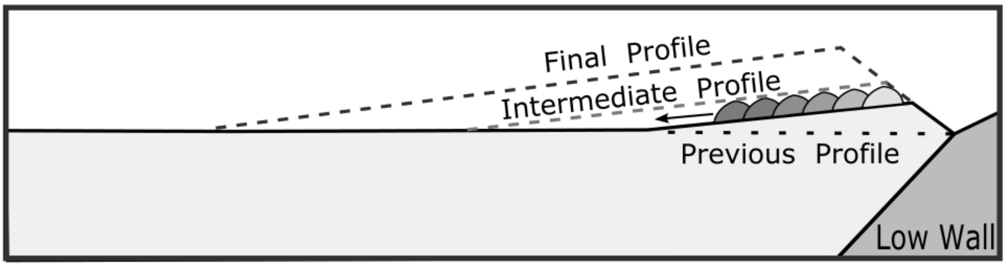
Secondary Actors: None.

Precondition: The void has been filled to level.

Main Success Scenario:

1. The *Dozer* begins a new lift by **Stacking** beginning at the low wall, with a length of approximately three stacks.
2. The *Dozer* **Flattens** the previously created lift until a new load can be pushed along the top of the previous lift without spilling from the edges of the blade.
3. The Dozer **ChangesSlots** to work in another slot which has not yet been backstacked.
4. Repeat 1-3 until all slots being worked by the dozer have been backatacked to the same level.
5. The *Dozer* begins a new lift by **Stacking,** beginning at the low wall, with a length extending to approximately two stacks beyond the end of the previous lift.
6. The *Dozer* **Flattens** the previously created lift until a new load can be pushed along the top of the previous lift without spilling from the edges of the blade. Some material naturally spills from the blade as the dozer transitions to the top of the previous stack, reducing the grade with successive pushes.
7. The Dozer **ChangesSlots** to work in another slot which has not yet been backstacked.

8. Repeat 1-3 until all slots being worked have been filled to the target dumping profile.



BackStackUphill Figure 1: Backstacking Uphill

OL 10 CleanHighwallWithExcavator

Traces From

ProgressiveGradeCutting
ConstantGradeCutting

Goal: To remove fragmented material adjacent to the highwall, creating a clean, hard highwall surface and to spoil all material as far as possible into the dozer area without creating high piles which would be difficult to remove by dozers.

Brief Description: The Highwall Excavator performs a pass along the length of the highwall, removing one flitch of material(the most efficient depth for an excavator to remove in one pass). The excavator cuts loose material from the highwall, until a regular profile of hard rock at the design angle is achieved. The material cut from the highwall and excavator bench is spoiled into the dozer area below the excavator bench to be pushed into the void. The excavator ensures that the spoil is spread rather than heaped to prevent excassively steep piles for the dozer to remove.
Primary Actor: *HighwallExcavator.*

Precondition: The dozers have lowered the overburden profile below the highwall excavator bench.

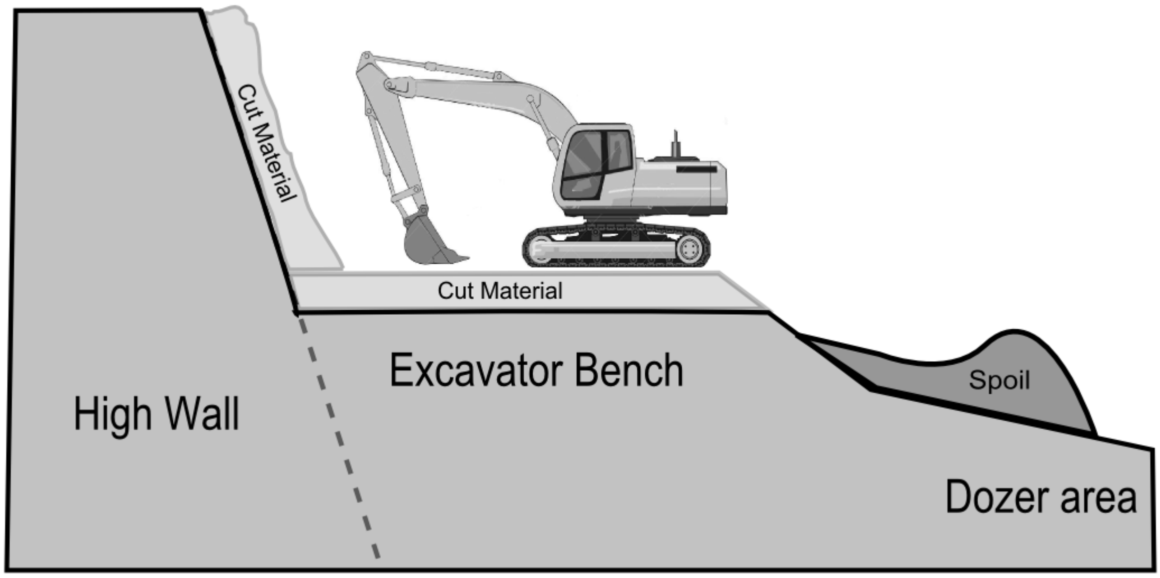
Main Success Scenario:

1. The *HighwallExcavator* enters the pit and travels to the excavator bench which has been established by the dozers at the rear of the slots.
2. The *HighwallExcavator* cuts material from against the high wall at the design angle and from the excavator bench, placing the spoil as far as possible into the dozer area as shown in CleanHighwallWithExcavatorFigure 1.
3. The *HighwallExcavator* repositions itself further along the high wall.
4. Repeat 2-3 until a depth of 1 excavator flitch has been removed from the excavator bench along the length of the strip.

Alternatives:

2a. There is especially loose material at the top of the high wall.

2a.1. The *HighwallExcavator* shapes the specified upper section of the high wall to 45 degrees to ensure stability.
2a.2. Return to 2.



CutAndCleanHighwall Figure 1: Excavator at highwall

OL 11 RemoveOverburdenWithExcavator

Traces From

DozerPivotPush

Goal: Remove the overburden material which remains above the to of coal by excavator.

Brief Description: An amount of overburden has been left above the top of coal as this material is more economically removed by excavator than bulldozer. The height of the bench is an integer multiple of the flitch depths of the excavator doing the removal. The *OverburdenExcavator* removes the remaining material in successive layers until the coal is exposed.

Primary Actor: *OverburdenExcavator*.

Secondary Actors: *HaulTruck.*

Precondition: Overburden above the excavator benches has been removed.

Main Success Scenario:

1. The *OverburdenExcavator* cuts material at a depth of one flitch and loads the material into a *HaulTruck.*
2. Repeat step 1 until the *HaulTruck* is full.
3. *HaulTruck* transports spoil to dump and another *HaulTruck* moves in to be loaded.
4. Repeat step 1 to 3 until the coal is exposed.

OL 12 ClearTopOfCoal

Traces From

DozerPivotPush

Traces To

SlotDozing
ChangeSlots
CrissCrossBermRemoval

Goal: Remove the overburden from the buffer zone and expose the surface of the coal seam.

Brief Description: The remaining small amount of material above the top of coal is removed by dozers. Back to front dozing is an inefficient method compared to front to back dozing but is used during the final buffer zone cleanup where the back to front method minimizes direct dozer contact with coal. The process is illustrated in ClearTopOfCoal Figure 1.

Primary Actor: *Dozer*

Secondary Actors: None.

Precondition: Overburden above the buffer zone has been removed.

Main Success Scenario:

1. The *Dozer* performs **a SlotDozingCycle** to remove the first cut from the rear of the slot.
2. The *Dozer* **ChangesSlots.**
3. repeat 1-2 until one cut has been made in every slot assigned to the *Dozer.*
4. The *Dozer* performs **CrissCrossBermRemoval.**
5. repeat 1-4 until the coal seam is entirely exposed.

ClearTopOfCoal Figure 1: Removal of Buffer Zone with Back to Front Slot Dozing

EO – Elemental Operation Use Cases

EO 1 SlotDozing

Traces From

EstablishWorkingGrade
ProgressiveGradeCutting

Traces To

CrissCrossBermRemoval
StraddleBerms
SlotDozingCycle
ChangeSlots

Goal: Remove material from the current slot through execution of a series of slot dozing cycles.

Brief Description: A slot dozing cycle consists of cutting, carrying, dumping and returning. A cutting length is the distance required to fill the dozer blade with material at a given depth. Successive cuts occur behind the previous cut, utilizing the slot as it develops to retain blade fill. A slot is complete when the berms on eather side of the Dozer have reached a height of once dozer blade. Once a slot is complete, the dozer moves to begin work in one of the adjacent slots. If all slots in the dozer's area are complete, the dozer begins straddling berms, to remove the previous berms and establish new slots along the centerline of the previous berms.

Primary Actor: *Dozer.*

Secondary Actors: None.

Precondition:

Main Success Scenario:

1. The *Dozer* performs a **SlotDozingCycle** with a cut which will remove the frontmost material remaining within the curent slot.
2. Repeat 1 until the berms at any point along the slot have reached a height of one blade.

3. The *Dozer* performs **ChangeSlots.**
4. Repeat 1-3 until all slots being worked by the dozer have reached a berm height of one dozer blade.
5. The *Dozer* performs **StraddleBerms** to establish a new slot along the centreline of a previous berm.
6. Repeat 5 until all previous berms have been removed, and new slots established in their place.
7. Repeat 1-6

Alternatives:

5a. The plan calls for slot locations to remain after berm clearing.

5a.1. The Dozer performs **StraddleBerms**

5a.2 The *Dozer* returns to the original slot to continue work.

5a.3. Return to 6.

EO 2 TipHeadSafely

Traces From

TipHeadLevel
TipHeadDownhill
TipHeadUphill

Traces To

Goal: Dump material from the end of a slot while always maintaining a load dumped at the end of the slot for safety.

Brief Description: An initial load is dumped at the top edge of the wall. On the following push, the second load is used to push the first, causing the first load to fall and to be replaced by the second. This continues until the desired dump profile using tip heading is achieved (TipHeadSafely Figure 1). This particular process is employed as a safety measure.

Primary Actor: *Dozer*.

Secondary Actors: None.

Precondition: The D*ozer* must push from a steep edge which is too high to be safely traversed.

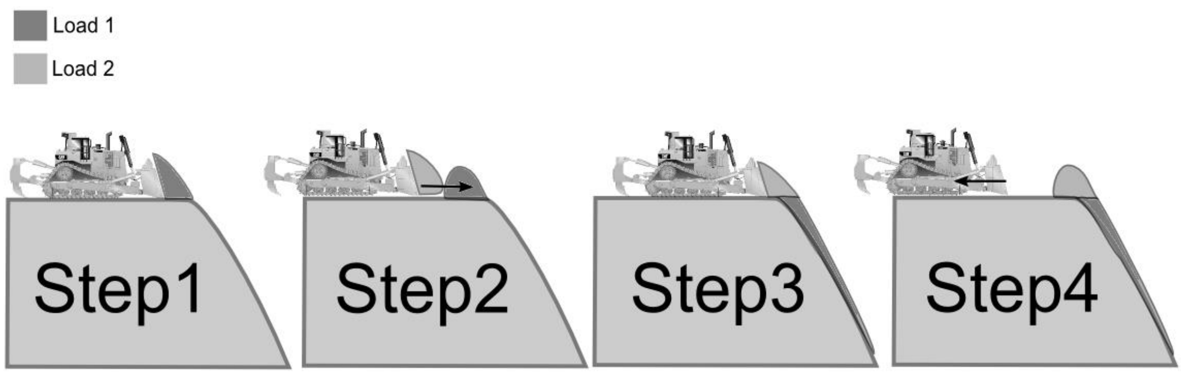
Main Success Scenario:

1. The *Dozer* carries and dumps a load at a point just before the tip heading edge.
2. The *Dozer* carries another load to the location of the previous load.
3. The *Dozer* uses the second load to push the first load off the tip heading edge.
4. The *Dozer* leaves the second load in place of the first load.

Alternatives:

1a. Tip head profile begins to subside when driven over.

1a.1 The *Dozer* reverses backwards from the edge until stable material is reached.
1a.2. Return to Step 1.



TipHeadSafely Figure 1

EO 3 SlotDozingCycle

Traces From

SlotDozing

Traces To

Goal: Cut, carry, and dump a single load of material with control assistance from *AutoBladeAssist (ABA).*

Brief Description: ABA is used to assist the operator with each major blade pose adjustment in the cut/carry/dump cycle.

Primary Actor: *Dozer*

Secondary Actors: *AutoBladeAssist*

Precondition: Standard slot dozing procedures are in progress.

Main Success Scenario:
1. The *Dozer* lowers and pitches the blade forward, and cuts from the current cutting location.
2. The *Dozer* pitches the blade backwards and carries to dump location.
3. The *Dozer* raises and pitches the blade, and dumps the load.
4. The *Dozer* reverses in the slot to return to the next cutting location.

EO 4 CrissCrossBermRemoval

Traces From

SlotDozing

Traces To

Goal: To move berm material to the dumping region while using the remaingin berms in fromt of ht edozer to contain the load.

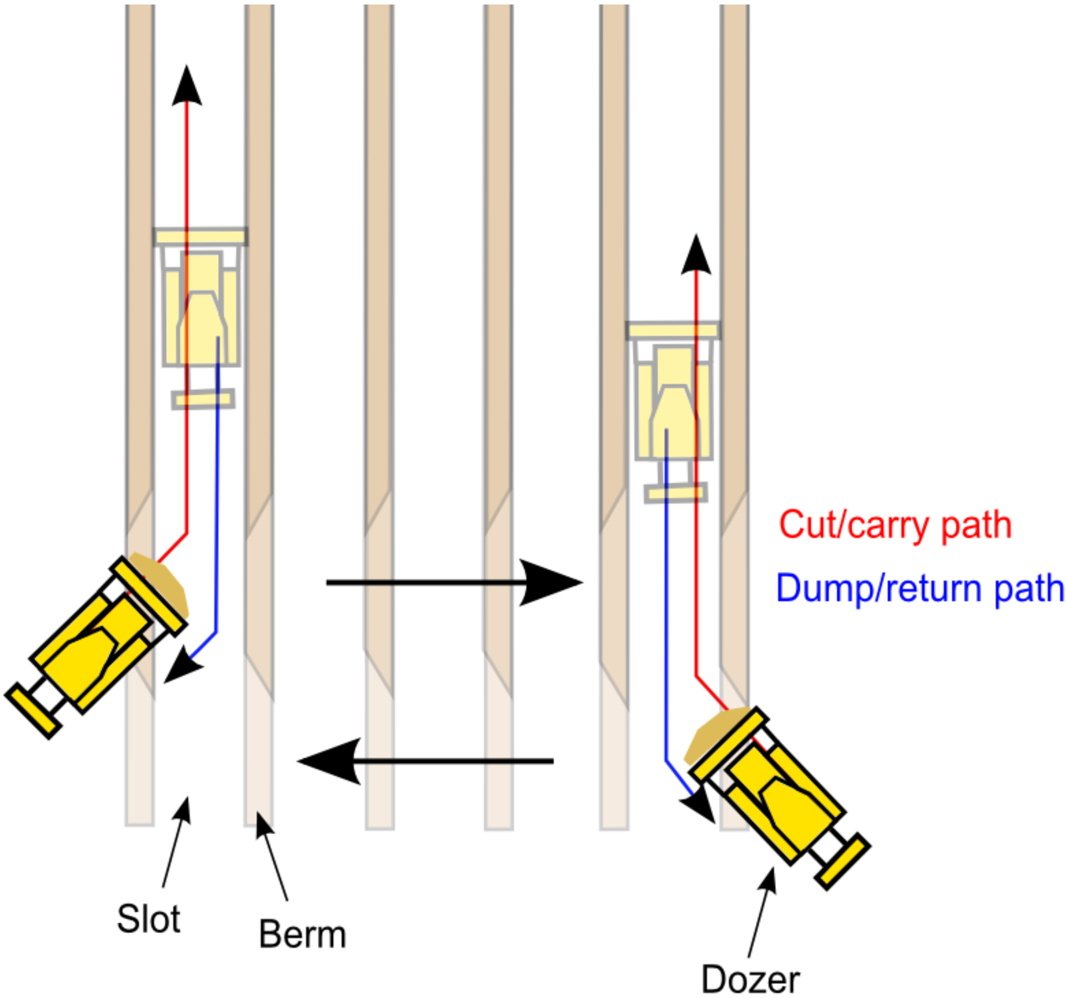
Brief Description: Berm removal is completed for multiple slots simultaneously. The cutting location is at the rearmost point on the berm on each slot and the material is pushed into an adjacent slot for carrying to dump location. The criss-cross method captures the full advantage of slot dozing by using the berms not yet removed to maintain blade fill (CrissCrossBermRemoval Figure 1).

Primary Actor: *Dozer.*

Precondition: The slot berms must be removed.

Main Success Scenario:

1. The *Dozer* reaches starting position at the rear of the edge-most berm to be removed, aligned at a 45 degree angle to the slot.
2. The *Dozer* performs a cut which passes through the slot berm at a diagonal, removing 10-15m of the slot berm, pushing into the adjacent slot.
3. The *Dozer* carries down the slot, then dumps according to the current dumping method.
4. repeat 1 - 3, beginning at the rear of each slot berm, and working across the breadth of the cutting region until the rearmost 10-15m has be removed from each berm.
5. repeat 1 - 4 until all berm material above the top of coal has been removed.



CrissCrossBermRemoval Figure 1: Criss Cross Berm Removal

EO 5 StraddleBerms

Traces From

SlotDozing

Traces To

Goal: To remove the material within an existing berm, establishing a new slot in its place.

Brief Description: The top of the slot berm is removed by the dozer performing one pass along its length. Material is pushed from the berm and falls to the side of the blade into the slots.

Primary Actor: *Dozer*

Secondary Actors: None.

Precondition: All slots assigned to the dozer have reached a depth of 1 blade height.

Main Success Scenario:

1. The *Dozer* reverses to the rear of the slot and aligns behind a berm.
2. The *Dozer* drives on top of the berm and performs a cutting pass along the length of the berm. Berm material is allowed to fall into the slots below.

EO .6 ChangeSlots

Traces From

SlotDozing

Goal: To move from a completed slot into another which is to be worked in.

Brief Description: The *Dozer* moves from the current slot into an adjacent on be passing along the excavator bench or pushing through a berm.

Primary Actor: *Dozer.*

Secondary Actors: *Highwall Excavator.*

Precondition: The current slot has berms up to one blade depth, but others are yet to be completed.

Main Success Scenario:

1. The *Dozer* reverses along the length of the slot and onto the excavator bench.
2. The *Dozer* drives into an adjacent slot.

Alternatives:

1a. Access to rear of slot is prevented by excavator or spoil pile.

1a.1.The *Dozer* reverses to within a safe distance of the rear of slot.
1a.2.The *Dozer* pushes through the slot berm to pass into the adjacent slot.
1a.4. Use case ends.

Glossary

BackStacking
A dumping method used to cause an increase in the grade of the dumping profile. Back stacking adds more material to the back of the dump region causing the grade to increase about the pivot point.

Berm
An earth wall which forms at both edges of a slot and acts to prevent spillage from a full blade. Berms must be removed only when a slot has reached a depth of 0.5-1 blade heights.

Buffer Zone
A shallow amount of overburden (0.3-0.5 m) which is left on top of the coal seam to minimize dozer contact damage to the coal.

Cast
The movement of overburden into the void as a result of blasting.

Flitch
The most efficient cutting depth for an excavator. This depends on the model and size of the excavator chaosen for the task. Overburden to be removed by excavator should be left at a depth which is a integer multiple of a the flich depth to ensure efficiency.

Grade
The angle of the overburden surface in a particular area relative to horizontal, measured as a percentage.

High wall
The sheer wall at the rear of the overburden removal area that is parallel to the strip.

Level
The elevation of the overburden surface in a particular area relative to the top of coal.

Lift
A layer of consecutive dumps which form part of a backstacking wedge.

Low wall
The wall of the void on the opposite side of the high wall, parallel to the strip.

Pivot Point
A boint identified on a 2D cross section of the strip to be at the level of the top of coal, intersecting a 45 degree line drawn from the bottom of the coal face to be mined. The pivot point is used as the

'pivot' when reducing the overburden grade in PogressiveGradeCutting or increasing the grade of the dump region during BackStacking.

Pivot push
A strip mining operation executed by teams of bulldozers which remove material from above a coal seam to be mined, dumping into the adjacent void through choreographed sequences of cuts and dumps.

Prime
Material which has been moved to its final target destination.

Power trough
A trough in the overburden which runs parallel to the strip and close to the high wall. The power trough may have steep edges which pose a hazard for dozers traversing the surface.

Slot dozing
A cutting method where dozers cut along the same line to form a slot. The edges of the slot are used to prevent the loads from spilling from the blade edges during carrying and improve efficiency.

Spoil
A pile of overburden material which has been dumped by an excavator.

Strip
Typically long narrow region which has been designated to be cleared of overburden to facilitate coal mining.

Target cutting profile
The desired geometry of the remaining overburden material upon finishing bulk dozer push operations.

Target dumping profile
The desired geometry of the dumped overburden material upon finishing bulk dozer push operation.

Tip Head
A dumping method where the load is pushed over a steep edge and allowed to fall naturally at the angle of repose.

Top of coal
The top surface of the coal seam which is to be uncovered.

Void
The area within the previous strip that was previously mined.

Working grade

A surface of the overburden which is at a grade shallow enough to be comfortably traversed by the bulldozer.

APPENDIX B

Aerial Survey, the calculation of terrain volumes, and estimates of volume error

Material volumes reported in this thesis are determined using photogrammetric methods based on photographs taken from an unmanned aerial vehicle. This appendix outlines the methodology used to obtain topographical aerial surveys and estimates the bounds of error on survey volume measurements.

Unmanned aerial vehicle

The survey platform used for the survey work of this thesis was a DJI Phantom 4 unmanned aerial vehicle, see Figure B.1. The Phantom 4 carries an in-built 12.4 Megapixel camera mounted on an actively-controlled gimbal. The camera can remain at a constant angle of pitch relative to the direction of gravity, independent of the aircraft's orientation. The UAV navigation system is based on uncorrected GNSS with a spatial precision of approximately 1.5m and is used in tracking a prescribed flight path. Images taken by the camera are saved along with the time and location from which they are taken. The technical specifications of the Phantom 4 are summarized in Table B.1.

Figure B.1: DJI Phantom 4.

Table B.1: DJI Phantom 4 technical specifications [DJI, 2016].

Parameter	Value
Mass	1380 g
Diagonal length (excluding propellers)	350 mm
Flight time per battery	28 minutes (approximately)
Vertical hover accuracy	± 0.5 m
Horizontal hover accuracy	± 1.5 m
Camera specification	1/2.3”
Effective pixels	1.4 Mp

Constructing 3D surface maps from aerial photographs

Aerial images for the terrain survey were obtained using a DJI Phantom 4 flying the pre-programmed path shown in Figure B.2. The UAV flew at an altitude of 50 m above ground at a velocity of 3 m/s, with the camera directed vertically down. Three hundred images were taken at regularly spaced intervals along the flight path.

A series of visible reference makers were placed in the work area and their positions surveyed using RTK-GNSS to a spatial precision of 0.1 m, see Figure B.3. The surveyed markers were used to improve the accuracy of the aerial survey relative to the survey reference frame, by ensuring that their known location aligned with their location as identified within the images.

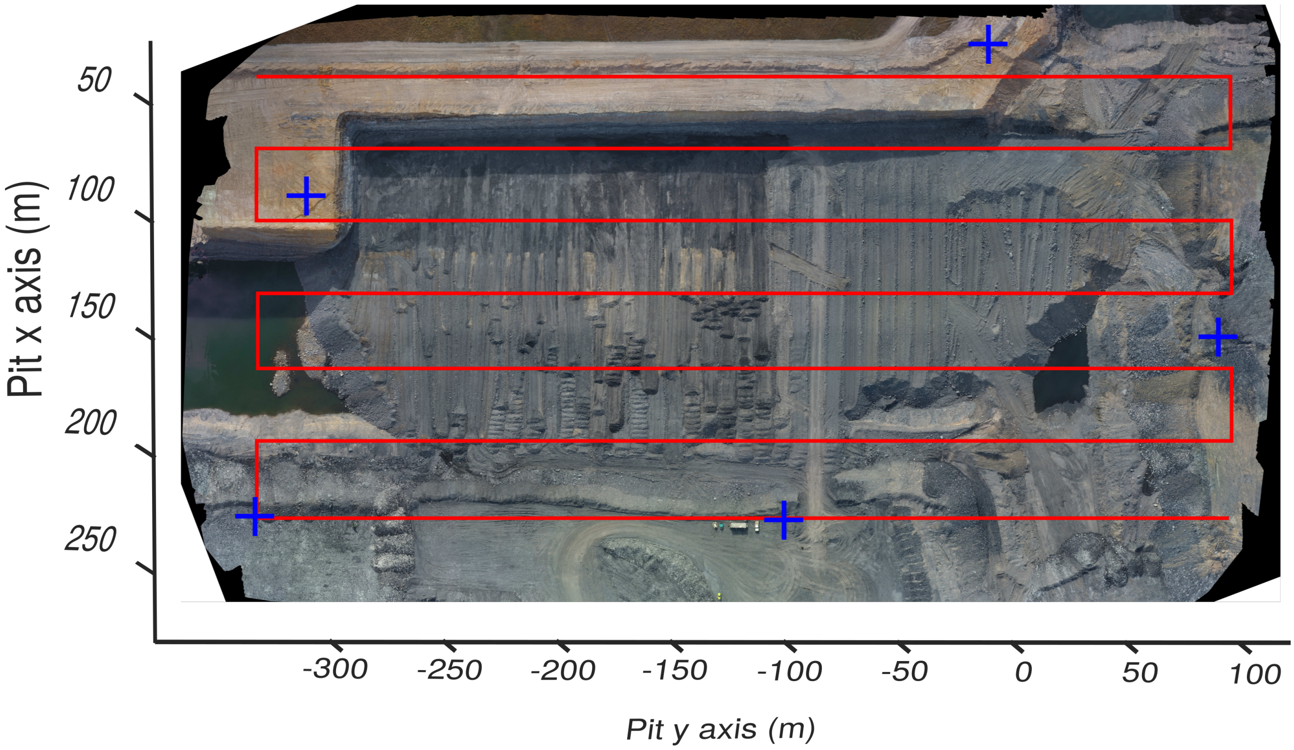


Figure B.2: A completed aerial survey (background) is shown with the flight path (red lines) of the UAV used to capture the images and the RTK-GNSS-located ground control points (blue crosses) used to localize the images within the survey frame. Approximately 300 aerial images were used in constructing this mosaic.

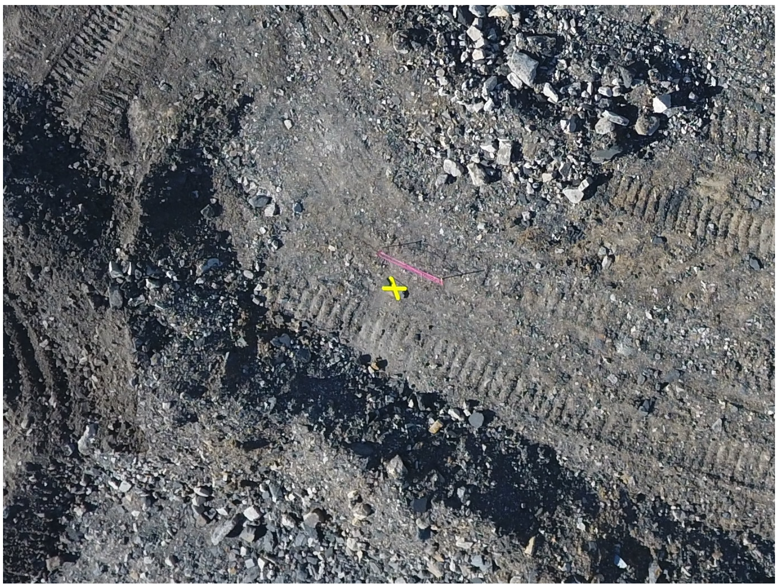


Figure B.3: A ground control marker as seen from one aerial image. The centre of this marker has already been localized using a high precision RTK-GNSS survey unit.

Commercial off-the-shelf photogrammetry software Pix4D Mapper [Pix4d, 2015] was used to reconstruct the terrain structure from the camera images. This software produced three dimensional point clouds subject to the processing parameters summarized in Table B.2. The point clouds output from Pix4D were then reduced to 1m $\times$ 1m height grids by averaging the height of all points within each cell. A typical survey height grid is shown in Figure B.4.

Table B.2: Photogrammetry settings used in Pix4d Mapper.

Parameter	**Setting**
Survey frame	MGA zone 55
Image down-sampling	1/2
Minimum number of shared matches for output point	2
Rolling shutter correction	on

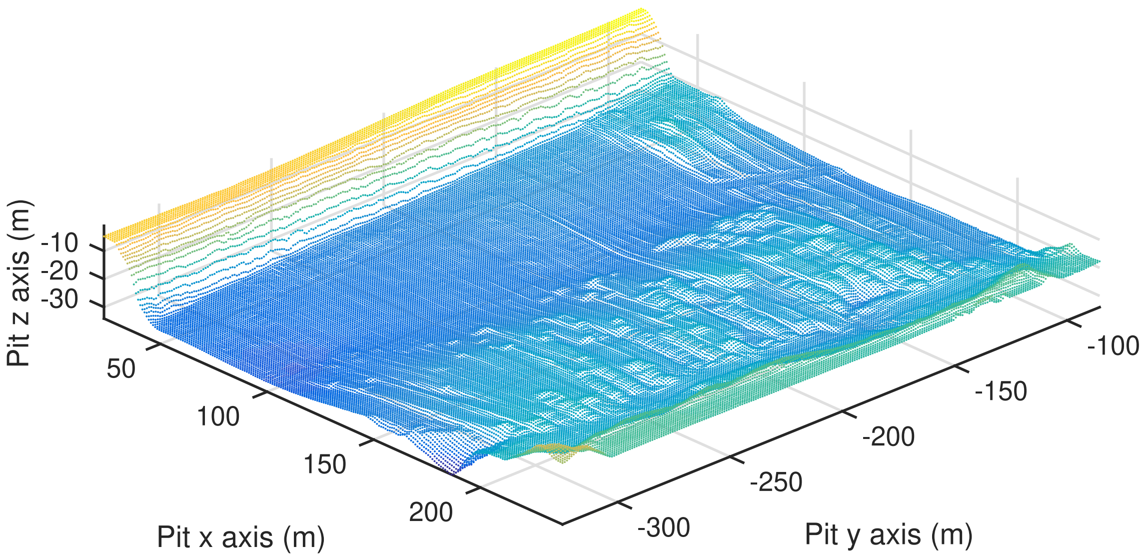


Figure B.4: The height grid associated with the terrain shown in Fig B.2. Each point in this figure represents the average height for all surveyed points within its 1m$\times$1m cell.

Error bounds on terrain volume calculations

An 12840 m^2 section of a strip was selected to determine the precision of terrain volumes. This area, shown in Figure B.5 did not change for several days following the completion of pivot push in the strip. Nine independent survey flights were conducted, each capturing the entire strip, including the selected area. A reference terrain grid was obtained by averaging the nine height grids.

Figure B.5: The area for the error test is bounded by the green rectangle.

Figure B.6 shows a colour map representing the error between measurement and the reference for one example survey. Larger errors are observed at the highwall. The reasons for the systematic distribution of errors may be associated with the near-vertical wall causing partial occlusion and shadowing of the floor. Note that despite the systemic error near the highwall, the majority of cells had a measured error significantly less than the maximum.

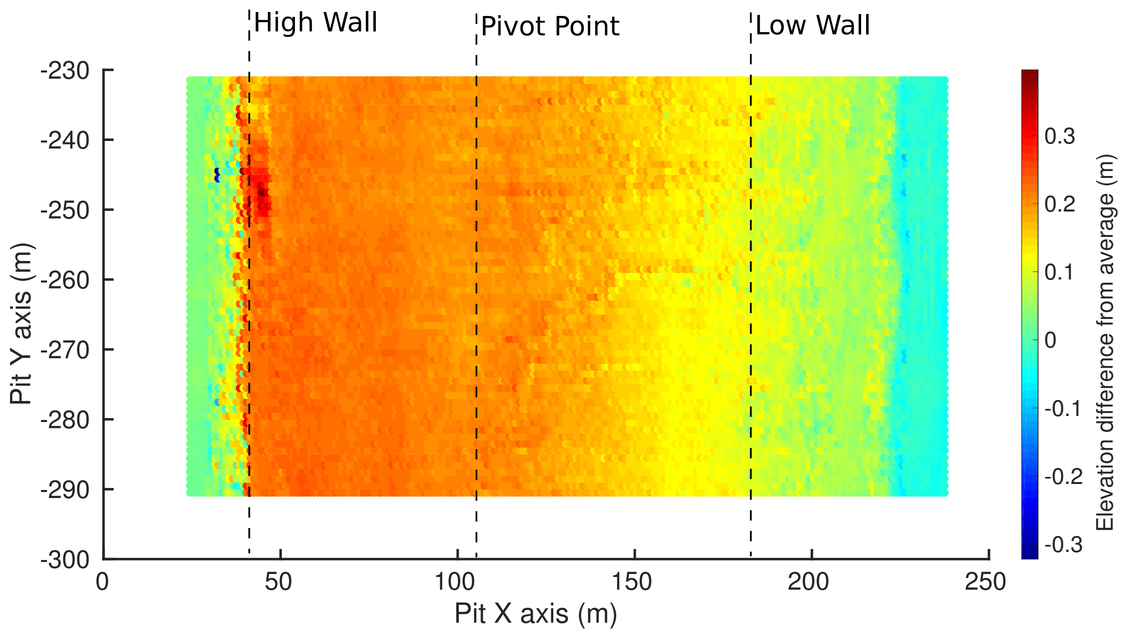


Figure B.6: Survey difference from reference for a typical survey. The high large error at coordinate $(47, 251)$ may be due to material falling from the high wall.

Figure B.7 shows the height difference distribution per square-meter cell for all of the nine surveys, showing that overall, most cells differ by less than 0.1m from the reference.

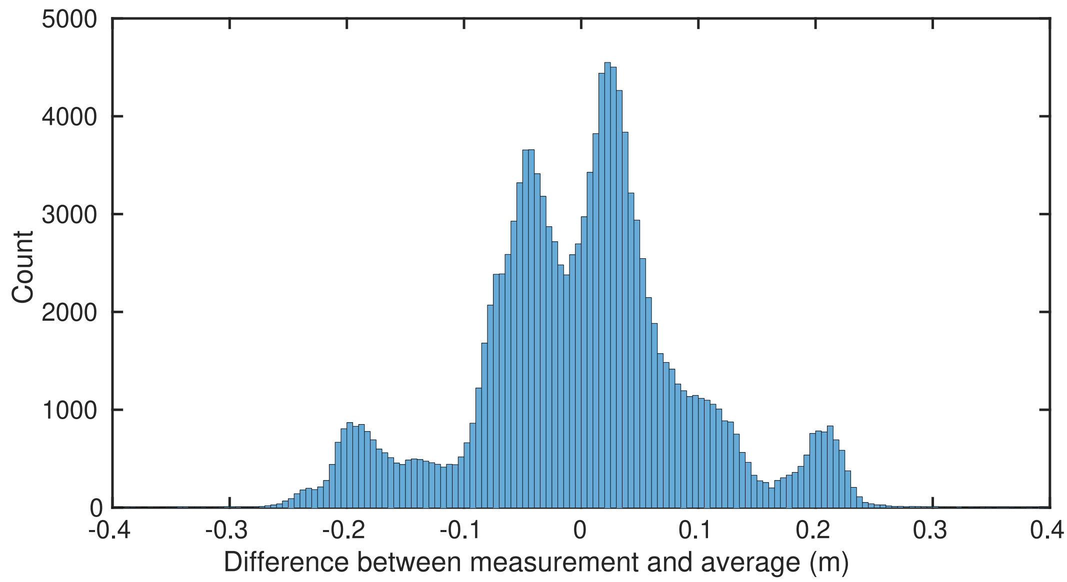


Figure B.7: Distribution of error for all nine surveys.

The volume movement calculations used in this thesis are determined on a whole-survey basis, therefore it was deemed appropriate to measure survey error over the entire survey rather than for individual cells. The volume difference between the two equally-sized height grids is computed as the sum of the per-cell difference in height, multiplied by the area of a cell.

The measurement uncertainty of each survey is determined as the total volume difference from reference and the results are shown in Table B.3. The per-survey volume difference from reference ranged between 1811.1m^3 and -1322.6m^3. Precision bounds per square-metre were obtained dividing by the area of 12840 m^2.

Table B.3: Volume error per survey. Maximum and minimum values are shown in bold.

Survey number	**Total Volume (m^3)**	**Volume difference from reference (m^3)**
1	92281.2	**1811.1**
2	89370.6	-1302.9
3	89988	-728.9
4	89358.8	**-1322.6**
5	90785.6	207.7
6	90242.8	-462.7
7	91371.3	847.7
8	90787.2	319.3
9	1133.6	631.2

The per-square meter bounds of measurement uncertainty are given in Table B.3. The error bars shown on productivity graphs in Chapters 2 and 4 are obtained by scaling the per-square-meter precision by the appropriate area.

Table B.4: Survey error values.

Metric	**Value**
Upper Error Bound	0.14m^3/m^2
Lower Error Bound	-0.10m^3/m^2

Appendix C

Recorded data channels

This appendix presents a summary of the data channels obtained during monitoring of Bulldozer 2010 and sample rates at which they were recorded.

Table C.1 lists the key data fields which are obtained from the bulldozer's control systems. Table C.2 lists the key data fields which are obtained from the autonomous system's pose solution. Table C.3 list all equipment status codes which were available in the Leica Jigsaw JDozer system.

Table C.1: Description of important data fields obtained from the machine control systems. These data fields are sampled at a rate of 10 Hz.

Source	**Data Field**
Torque Converter	Transmission Input Shaft Speed
Torque Converter	Percent Clutch Slip
Torque Converter	Transmission Output Shaft Speed
Torque Converter	Transmission Driveline Engaged
Engine ECM	Transmission Current Range
Engine ECM	Transmission Required Range
Engine ECM	Transmission Current Gear
Engine ECM	Transmission Actual Gear Ratio
Engine ECM	Transmission Selected Gear
Engine ECM	Actual Engine Percent Torque
Engine ECM	Drivers Demand Engine Percent Torque
Engine ECM	Engine Starter Mode
Engine ECM	Engine Speed

Table C.1: Description of important data fields obtained from the machine control systems. These data fields are sampled at a rate of 10 Hz.

Source	**Data Field**
Engine ECM	Engine Torque Mode
Engine ECM	Engine Demand Percent Torque
Engine ECM	Desired Engine Speed
Engine ECM	Throttle Position
Engine ECM	Engine Average Fuel Economy
Engine ECM	Engine Instantaneous Fuel Economy
Engine ECM	Engine Fuel Rate
Engine ECM	Engine Throttle Pos
IMU	Yaw Rate
IMU	Roll Rate
IMU	Pitch Rate
IMU	Vertical Acceleration
IMU	Longitudinal Acceleration
IMU	Lateral Acceleration
IMU	Roll/Pitch Latency
IMU	Roll Angle
IMU	Pitch Angle
Powertrain ECM	Brake pedal position
Powertrain ECM	Park brake status
Powertrain ECM	Left brake control current
Powertrain ECM	Right brake control current
Powertrain ECM	Left clutch control current
Powertrain ECM	Right clutch control current
Implement ECM	Blade Pitch Cylinder Extension
Implement ECM	Blade raise control current
Implement ECM	Blade lower control current
Implement ECM	Blade tilt left control current
Implement ECM	Blade tilt right control current
Implement ECM	Blae Pitch control current
Implement ECM	Ripper raise control current
Implement ECM	Ripper lower control current

Table C.1: Description of important data fields obtained from the machine control systems. These data fields are sampled at a rate of 10 Hz.

Source	Data Field
Implement ECM	Ripper shank in control current
Implement ECM	Ripper shank out control current
Implement ECM	Implement lockout control current
Implement ECM	Left Lift cylinder extension
Implement ECM	Right lift cylinder extension

Table C.2: Description of important data fields obtained from the autonomous system pose solution. These data fields are sampled at a rate of 50 Hz.

Description	Time Category
Filtered Pose Solution	Pitch
Filtered Pose Solution	Pitch RMS Error
Filtered Pose Solution	Pitch Rate
Filtered Pose Solution	Pitch Rate RMS Error
Filtered Pose Solution	Roll
Filtered Pose Solution	Roll RMS Error
Filtered Pose Solution	Roll Rate
Filtered Pose Solution	Roll Rate RMS Error
Filtered Pose Solution	Heading
Filtered Pose Solution	Heading RMS Error
Filtered Pose Solution	Yaw Rate
Filtered Pose Solution	Yaw Rate RMS Error
Filtered Pose Solution	Ground Speed
Filtered Pose Solution	Ground Speed RMS Error
Filtered Pose Solution	Longitudinal Acceleration
Filtered Pose Solution	Elevation
Filtered Pose Solution	Easting
Filtered Pose Solution	Northing
Filtered Pose Solution	GPS Low Accuracy Detected
Filtered Pose Solution	Track Speed

Table C.3: Description of all time codes used by the Leica JDozer equipment monitoring system.

Description	Time Category
Keylah Dust	Condition Delay
Sponcom Control	Condition Delay
Bogged	Condition Delay
Dust	Condition Delay
Fog	Condition Delay
Lightning	Condition Delay
No Electrical Power - Unscheduled	Condition Delay
Noise	Condition Delay
Rain	Condition Delay
Stuck/Jammed Bit	Condition Delay
Swap Operator	Idle/Standby
Wait Crib Trucks	Idle/Standby
Wait Loading Unit	Idle/Standby
Wait on Bin	Idle/Standby
Blocked Access	Idle/Standby
Move for Blasting	Idle/Standby
No Push Available	Idle/Standby
No Trucks	Idle/Standby
Not Required	Idle/Standby
Returned From Maintenance	Idle/Standby
Wait Drill Prep	Idle/Standby
Wait Lighting Plant	Idle/Standby
Wait on Down Equipment	Idle/Standby
Wait on Service Truck	Idle/Standby
Wait On Survey/Design	Idle/Standby
Wait on Survey/Pattern	Idle/Standby
Wait Shot Ground	Idle/Standby
Wait Support Equipment	Idle/Standby
Maintenance Postponed - Financial	Maintenance-Planned
Major Overhaul	Maintenance-Planned
Planned	Maintenance-Planned
Scheduled Maintenance	Maintenance-Planned

Table C.3: Description of all time codes used by the Leica JDozer equipment monitoring system.

Description	**Time Category**
Testing & Commissioning - Scheduled	Maintenance-Planned
Washdown - Scheduled Maintenance	Maintenance-Planned
Electric Drive And Control	Maintenance-Electrical
Electrical System Repair	Maintenance-Electrical
Lighting Repairs	Maintenance-Electrical
Machine Electronic Control	Maintenance-Electrical
Monitoring Systems	Maintenance-Electrical
Monitoring System	Maintenance-Electrical
Accident Damage	Maintenance-Mechanical
Air Conditioner System Repair	Maintenance-Mechanical
Air Induction & Exhaust	Maintenance-Mechanical
Air System Repair	Maintenance-Mechanical
Automatic Lube System Repair	Maintenance-Mechanical
Blade Repair	Maintenance-Mechanical
Braking System Repair	Maintenance-Mechanical
Bucket Repair	Maintenance-Mechanical
Chassis And Frame Repair	Maintenance-Mechanical
Dump Body Repair	Maintenance-Mechanical
Engine Cooling System	Maintenance-Mechanical
Engine Repair	Maintenance-Mechanical
Fire Suppression System Repair	Maintenance-Mechanical
General Machine Repair	Maintenance-Mechanical
Grader & Other Impliment Controls	Maintenance-Mechanical
Ground Engaging Tools (GET)	Maintenance-Mechanical
Hydraulic Hoses/Lines Repair	Maintenance-Mechanical
Hydraulic System Repair	Maintenance-Mechanical
Ladder Access Systems Repair	Maintenance-Mechanical
Maintenance Inspection	Maintenance-Mechanical
Mast Assembly Repairs	Maintenance-Mechanical
Mechanical	Maintenance-Mechanical
Mechanical Drive	Maintenance-Mechanical
Operator Station Repair	Maintenance-Mechanical

Table C.3: Description of all time codes used by the Leica JDozer equipment monitoring system.

Description	Time Category
Powertrain Repair	Maintenance-Mechanical
Rework	Maintenance-Mechanical
Service Body Maintenance	Maintenance-Mechanical
Steering System	Maintenance-Mechanical
Suspension System Repair	Maintenance-Mechanical
Swing System Repair	Maintenance-Mechanical
Tyre Repairs	Maintenance-Mechanical
Undercarriage Repair	Maintenance-Mechanical
Unscheduled Maintenance Setup	Maintenance-Mechanical
Washdown - Unscheduled Maintenance	Maintenance-Mechanical
Water Spray System	Maintenance-Mechanical
Water Trap	Maintenance-Mechanical
Unplanned	Maintenance Delay
Wait Labour	Maintenance Delay
Wait Parts	Maintenance Delay
Wait Support Resource	Maintenance Delay
Clean Active Face	Non-Productive
Pulling Batters	Non-Productive
Reposition in Face	Non-Productive
Attend Plant	Non-Productive
Coal Clean Up	Non-Productive
Drill Preparation	Non-Productive
Dump Maintenance	Non-Productive
Other Works	Non-Productive
Push to Loading Unit	Non-Productive
Rehabilitation	Non-Productive
Roadwork General	Non-Productive
Major Walk	Non-Productive
Operator Training	Non-Productive
Sidecasting	Non-Productive
Trenching	Non-Productive
Cab Cleaning	Operational Delay

Table C.3: Description of all time codes used by the Leica JDozer equipment monitoring system.

Description	Time Category
Crib	Operational Delay
Fill Drill Water	Operational Delay
Pre-Start Inspection	Operational Delay
Refuelling	Operational Delay
Shift Change	Operational Delay
Blasting	Operational Delay
Clean Tray/Bucket/Tracks	Operational Delay
High Tkph	Operational Delay
Machine Checks	Operational Delay
Move for Maintenance	Operational Delay
Opportune	Operational Delay
Refill Lube	Operational Delay
Refill Water	Operational Delay
Replace GET / Bit	Operational Delay
Wash Equipment	Operational Delay
Hot Seating Other Equipment	Process Delay
Personal Break	Personnel delay
Fatigue Break	Personnel delay
Full Inspection	Personnel delay
Meetings & Communications	Personnel delay
No Operator	Personnel delay
Safety / Incident	Personnel delay
Bench Preparation	Productive
Prime Push	Productive
Prime Push Autonomous	Productive
Prime Push RC	Productive
Prime Push Partings	Productive
Ripping Coal	Productive
Ripping Overburden	Productive
Ripping Partings	Productive
Stockpile Product	Productive
Stockpile ROM	Productive

Table C.3: Description of all time codes used by the Leica JDozer equipment monitoring system.

Description	**Time Category**
10.5 Hour Night Shift	Unscheduled
Equipment Parked	Unscheduled
Not Scheduled To Operate	Unscheduled
Public Holiday	Unscheduled

APPENDIX D

Comparison between measured and simulated pivot push

This appendix explores the similarities and differences between what was measured in the validation trial and what was simulated using the pivot push simulation framework. Sections of this appendix are referenced in Chapter 2.

Cutting and dumping locations

The following figures (D.1-D.6) compare the progression of cutting and dumping locations between measurement and simulation for each of the three methods.

The following observations are made;

- Measured operation: The tip heading dumping strategy is visible through the steady progression of dumping locations. Back stacking is identifiable as sharply descending vertical lines.
- Simulated operation: The tip heading dumping strategy is visible through the steady progression of dumping locations. Back Stacking is less identifiable than in the measured operation, due to a greater number of flattening cycles which alter the progression of dumping locations.

D.1 Cutting and dumping locations

Method 1

Figures D.1 and D.2 compare the progression of cutting and dumping locations while completing Method 1.

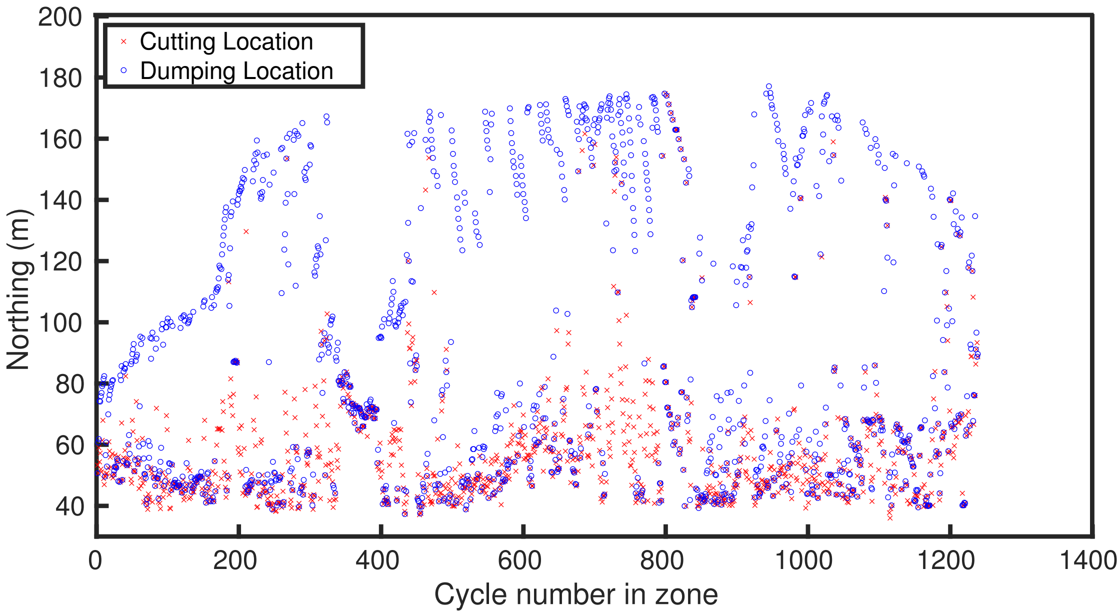


Figure D.1: Measured cutting and dumping locations in zone 1.

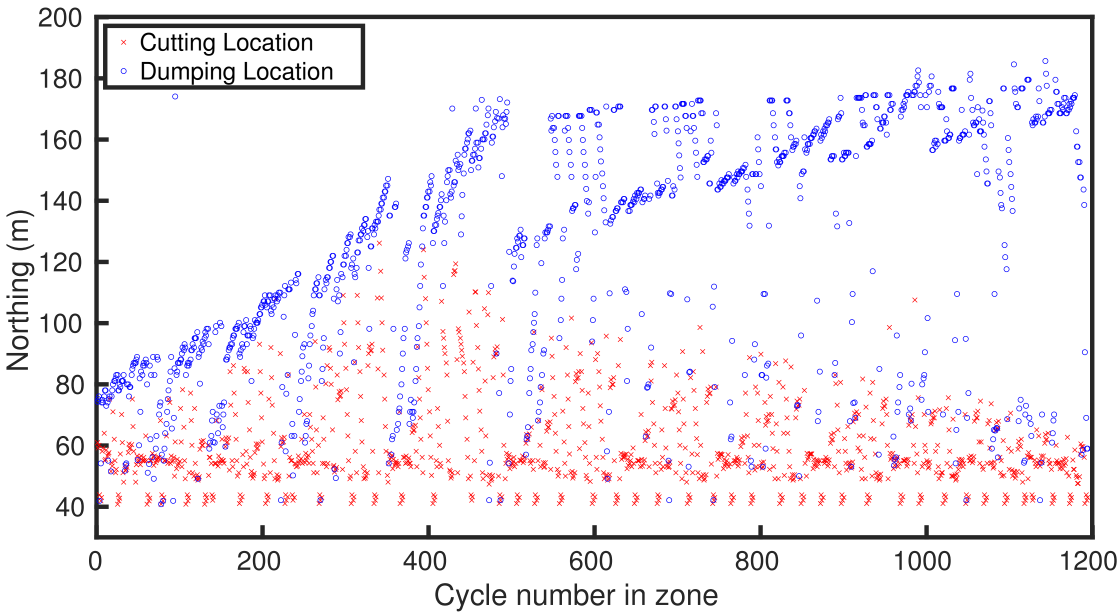


Figure D.2: Simulated cutting and dumping locations in zone 1.

Method 2

Figures D.3 and D.4 compare the progression of cutting and dumping locations while completing Method 2.

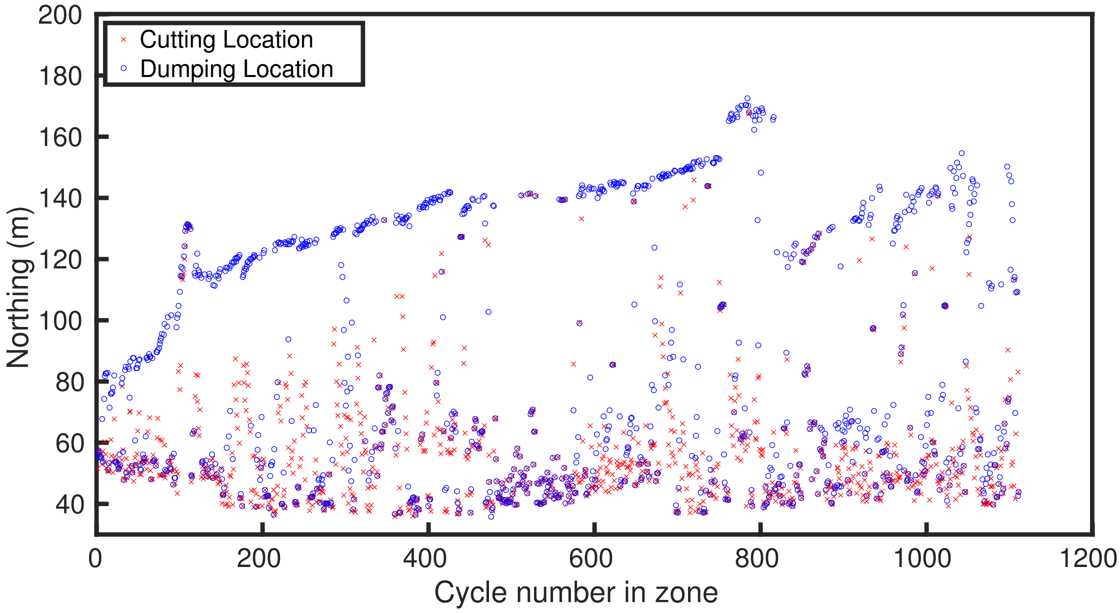


Figure D.3: Measured cutting and dumping locations in zone 2.

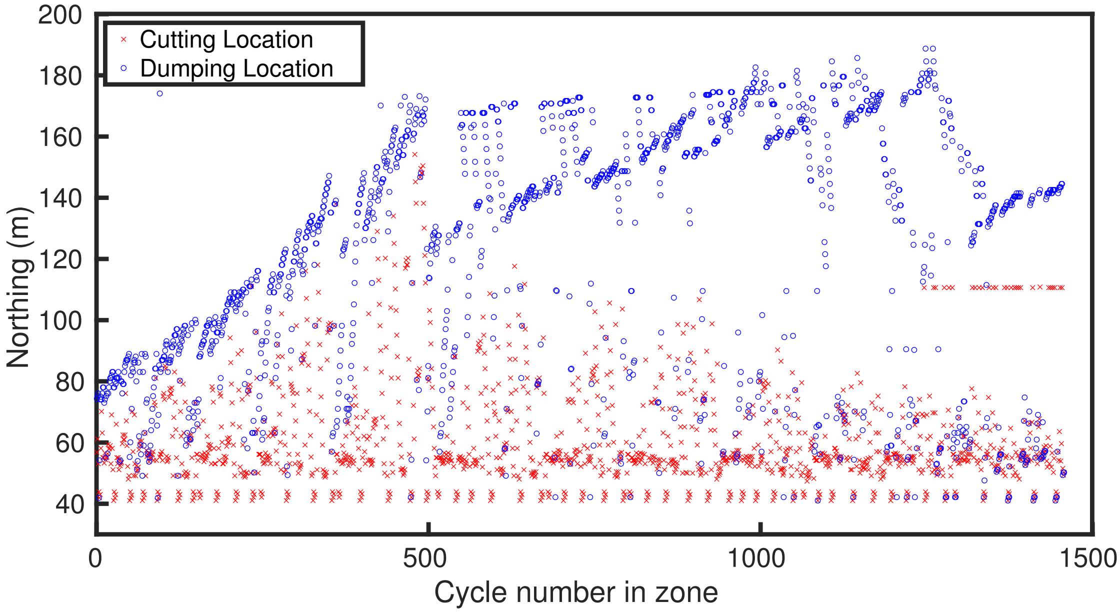


Figure D.4: Simulated cutting and dumping locations in zone 2.

Method 3

Figures D.5 and D.6 compare the progression of cutting and dumping locations while completing Method 3.

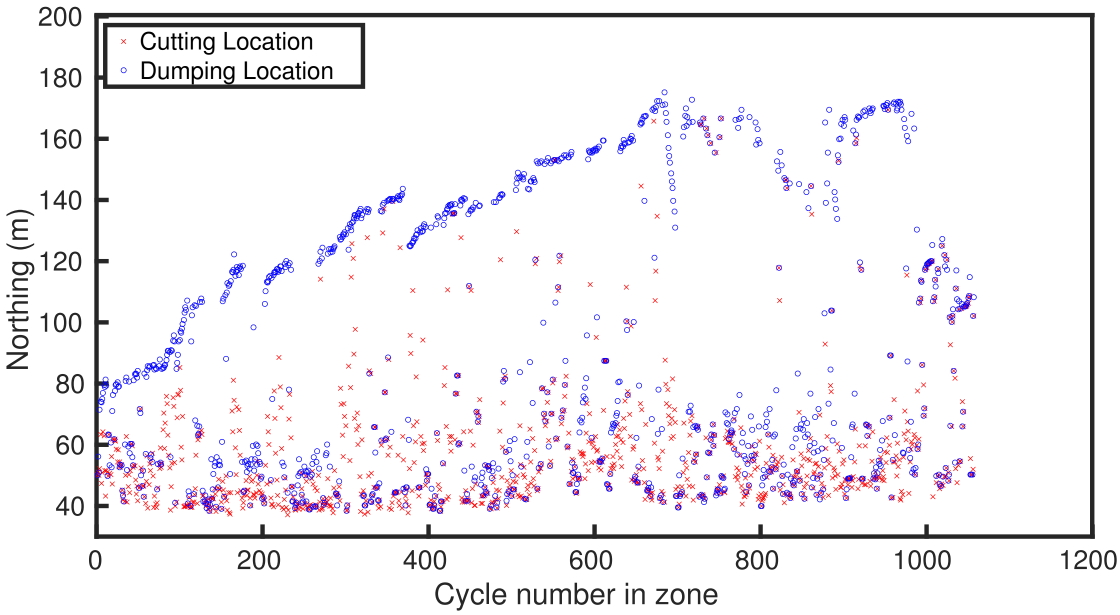


Figure D.5: Measured cutting and dumping locations in zone 3.

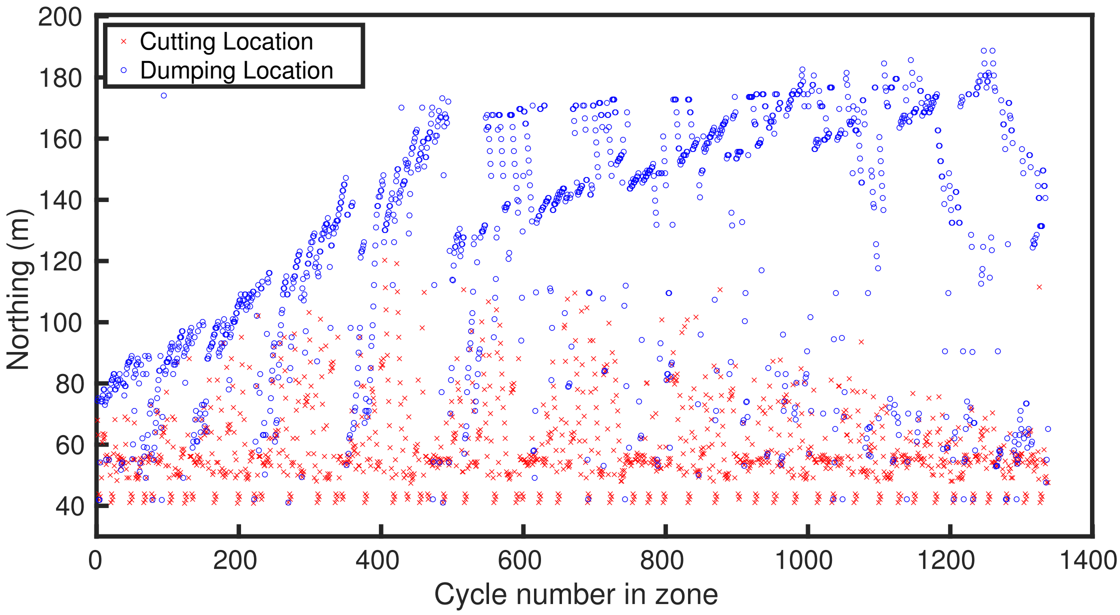


Figure D.6: Simulated cutting and dumping locations in zone 3.

Travelling velocity

The following figures (D.7-D.12) compare measured travelling velocities against simulation for each of the three methods.

The following observations are made:

- Manual operation was subject to a greater average velocity of travel than was predicted from simulation.
- The distribution of manual reversing velocities has multiple peaks corresponding to travel in first and second gear reverse, while the simulation has only a single peak of reversing velocity.
- The simulation is subject to less variance than the manual operation.

Method 1

Figures D.7 and D.8 compare the travelling velocities while completing Method 1.

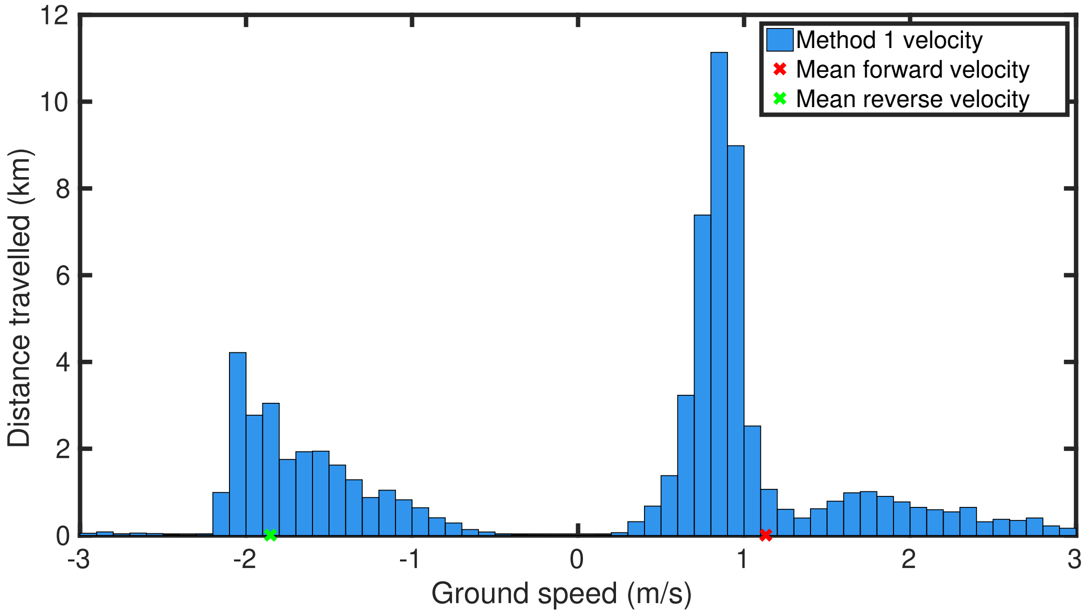


Figure D.7: Measured travelling velocities in zone 1.

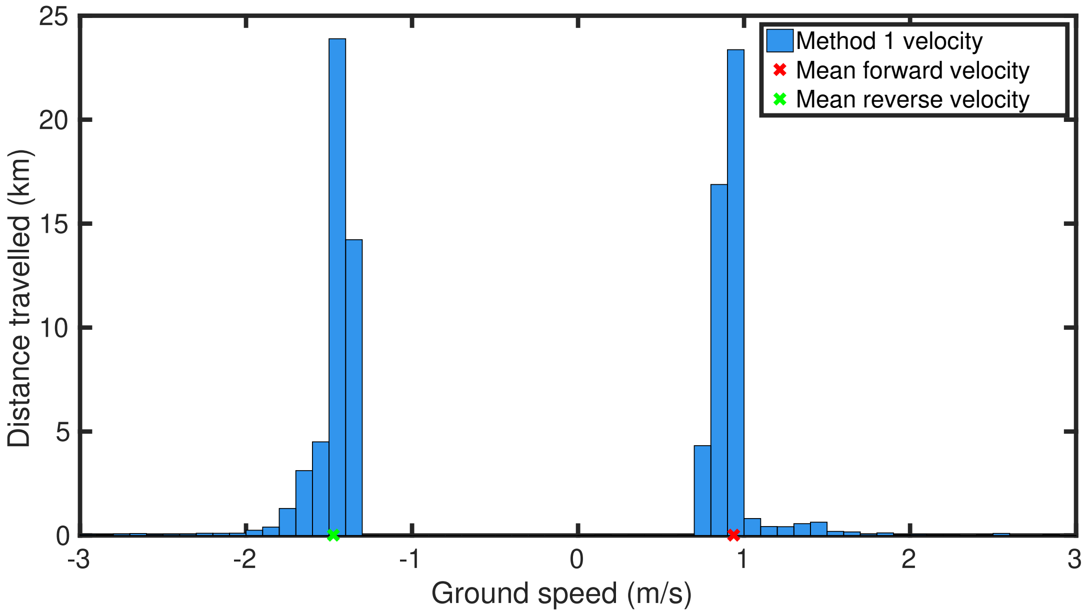


Figure D.8: Simulated travelling velocities in zone 1.

Method 2

Figures D.9 and D.10 compare the travelling velocities while completing Method 2.

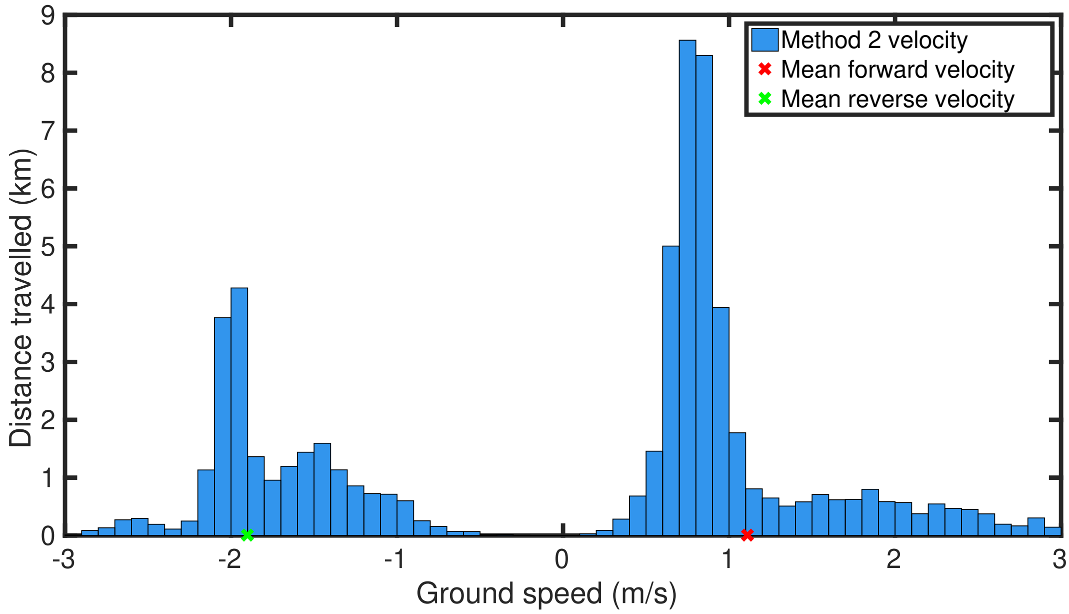


Figure D.9: Measured travelling velocities in zone 2.

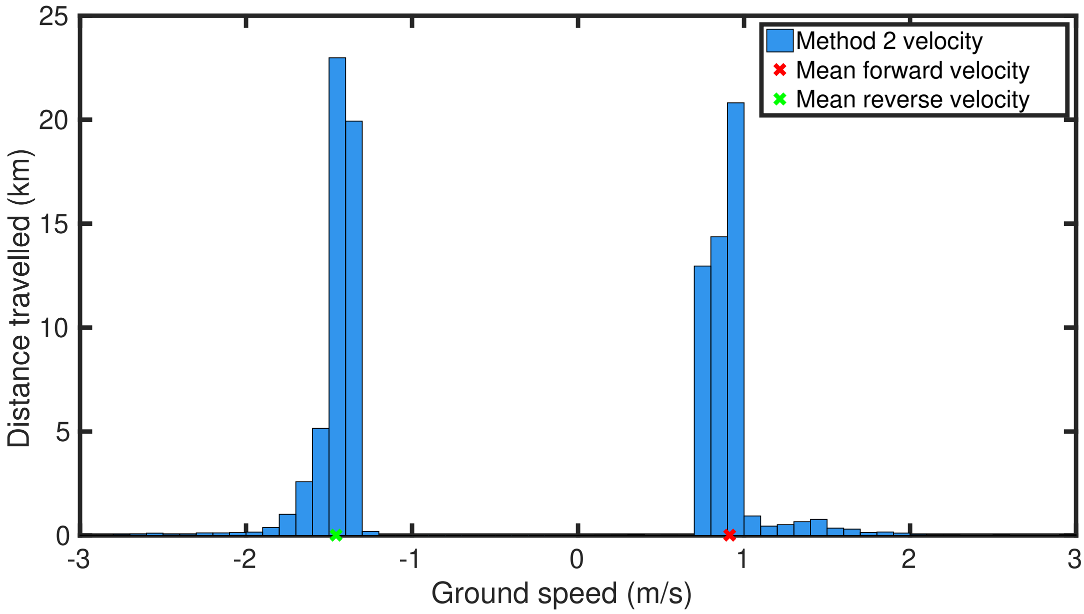


Figure D.10: Simulated travelling velocities in zone 2.

Method 3

Figures D.11 and D.12 compare the travelling velocities while completing Method 3.

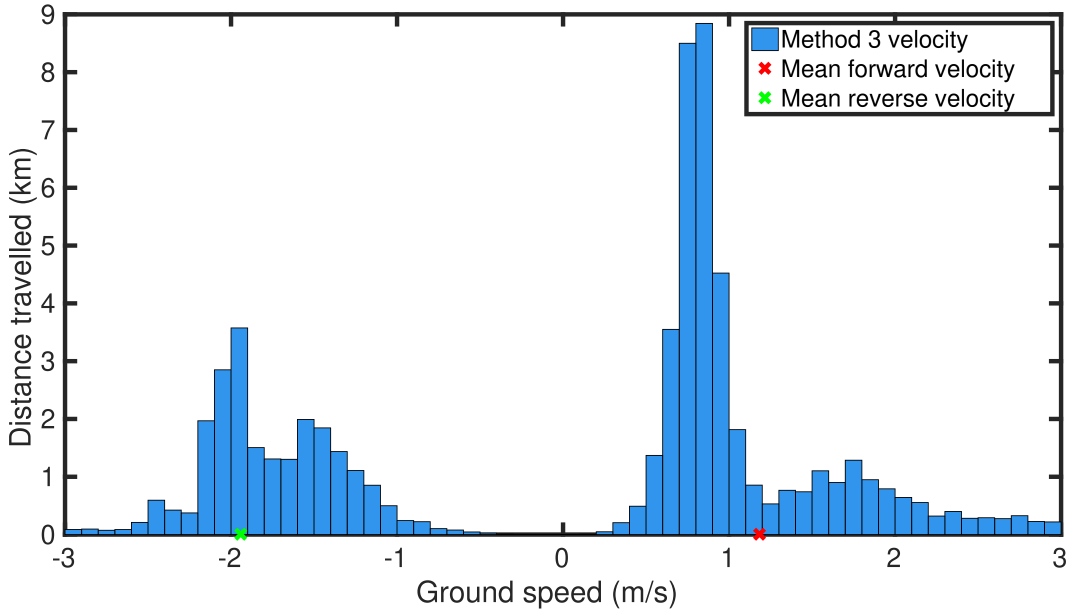


Figure D.11: Measured travelling velocities in zone 3.

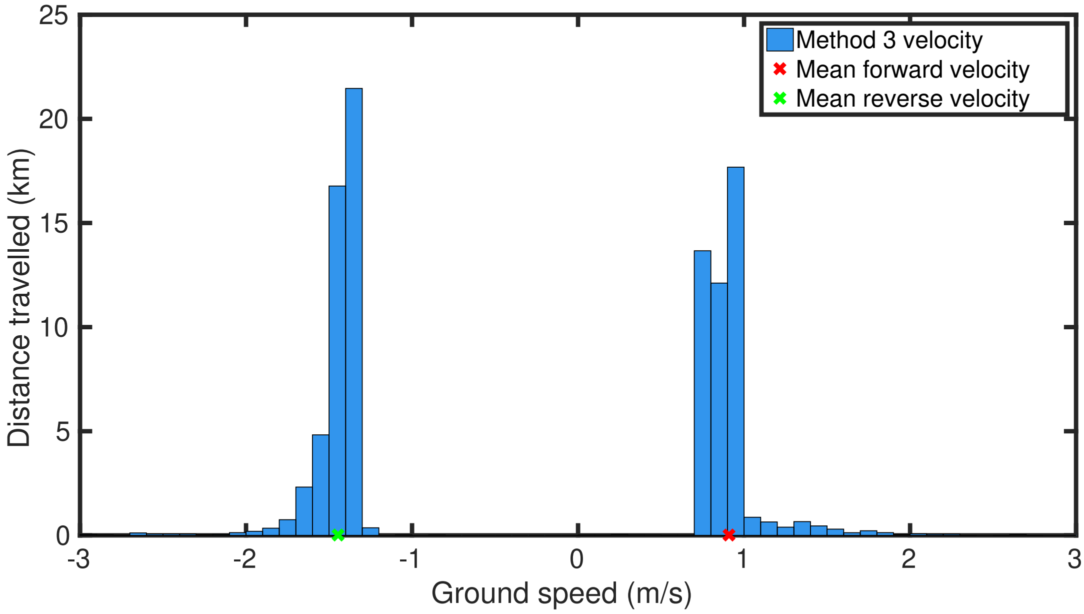


Figure D.12: Simulated travelling velocities in zone 3.

Travelling grade

The following figures (D.13-D.18) compare measured travelling grades against simulation for each of the three methods.

The following observations are made;

- Simulation produces consistently-graded terrain profiles. The simulation adheres to a -25% downhill grade when possible, which results in a corresponding peak in the grade distribution.
- The measured grades of travel are significantly more variable.
- The mean grade of travel aligns well between measured and simulated.

Method 1

Figures D.13 and D.14 compare the travelling grades while completing Method 1.

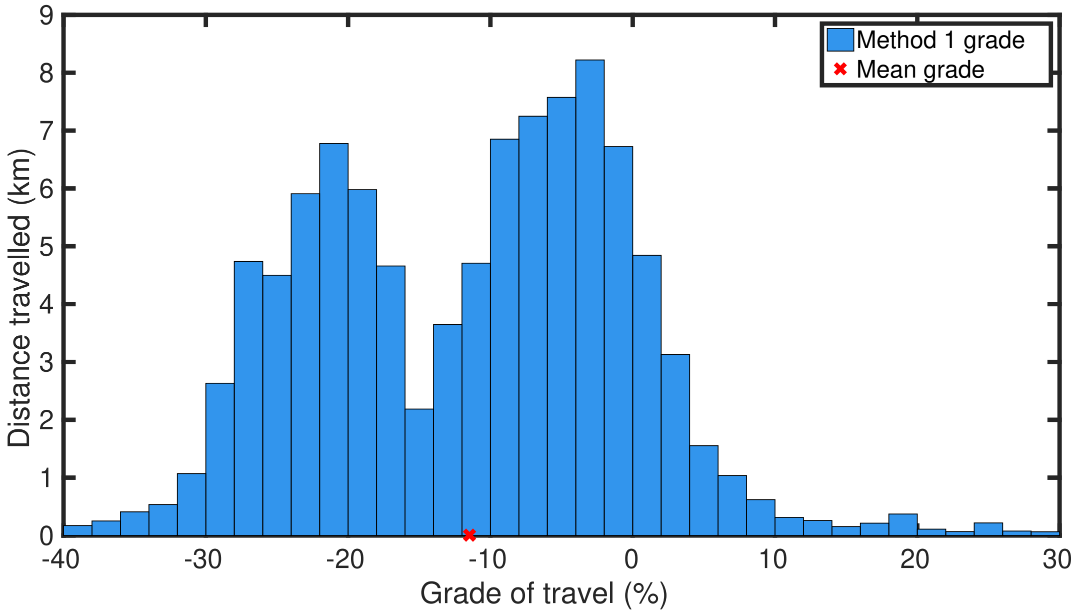


Figure D.13: Measured travelling grades in zone 1.

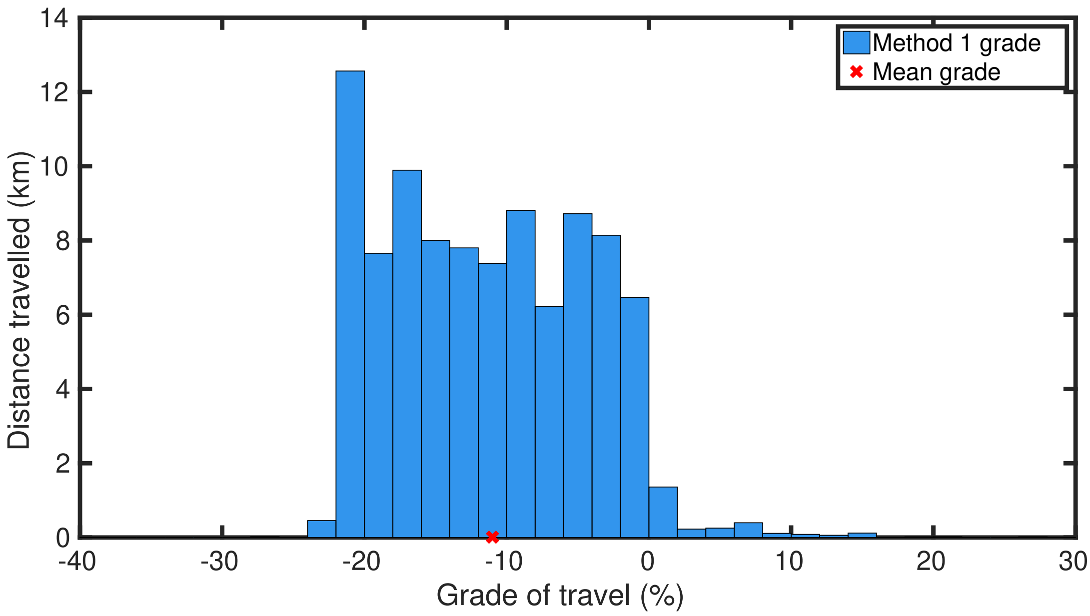


Figure D.14: Simulated travelling grades in zone 1.

Method 2

Figures D.15 and D.16 compare the travelling grades while completing Method 2.

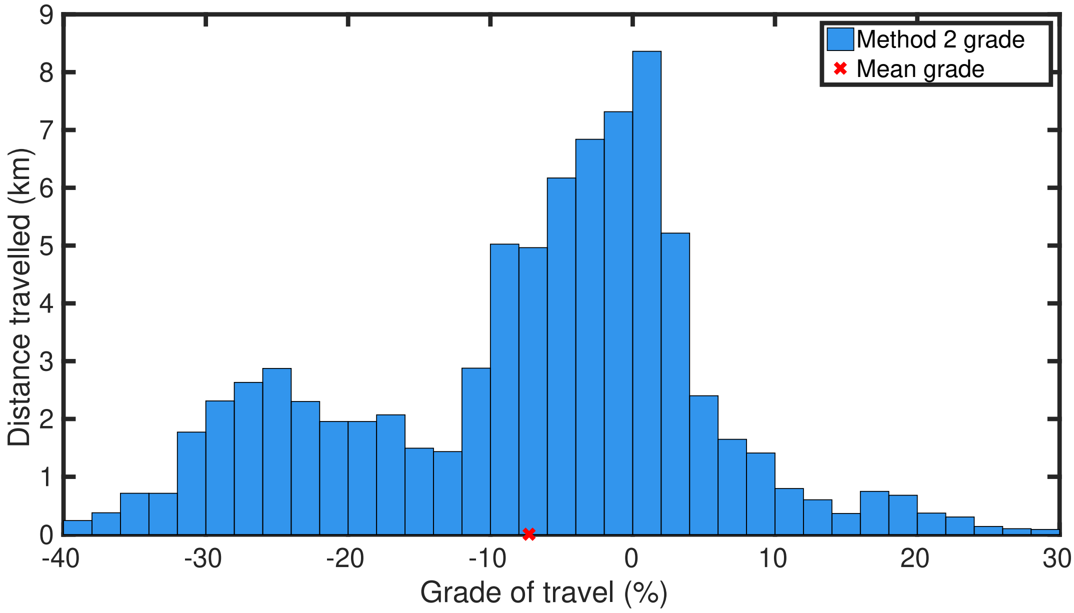


Figure D.15: Measured travelling grades in zone 2.

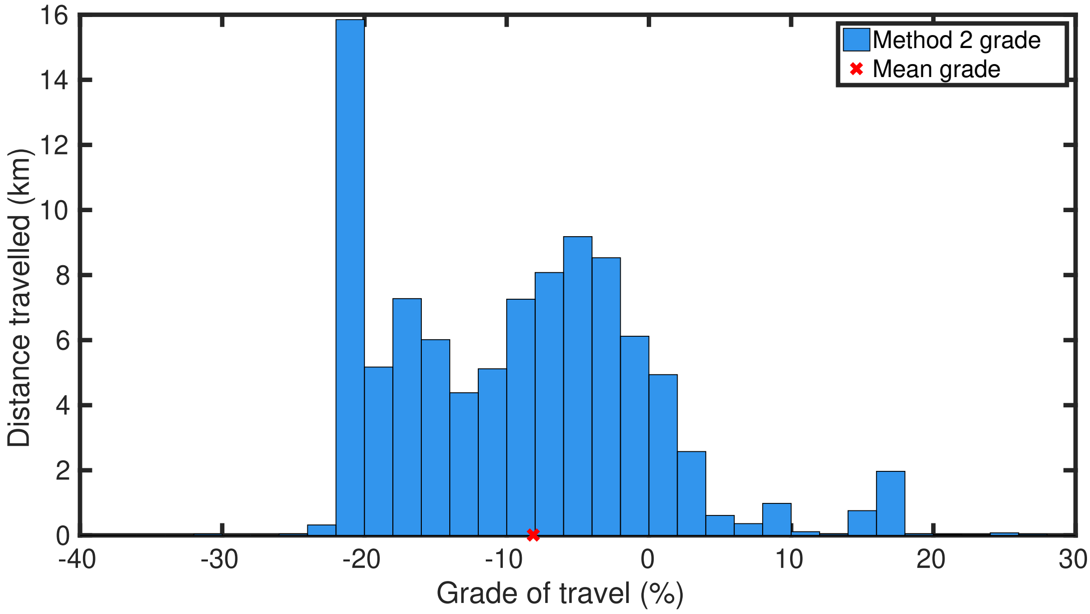


Figure D.16: Simulated travelling grades in zone 2.

Method 3

Figures D.17 and D.18 compare the travelling grades while completing Method 3.

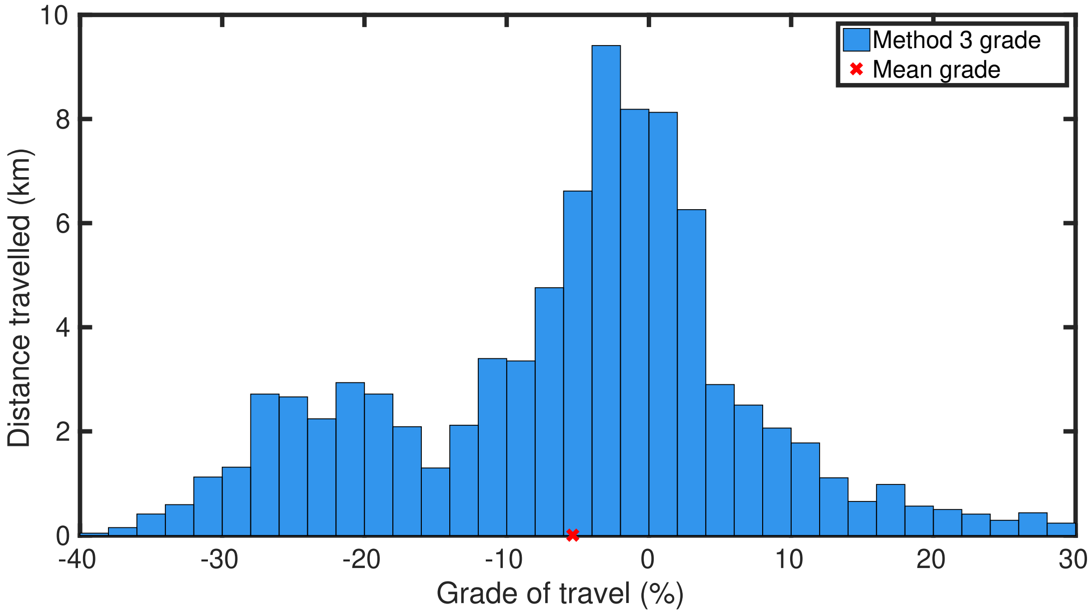


Figure D.17: Measured travelling grades in zone 3.

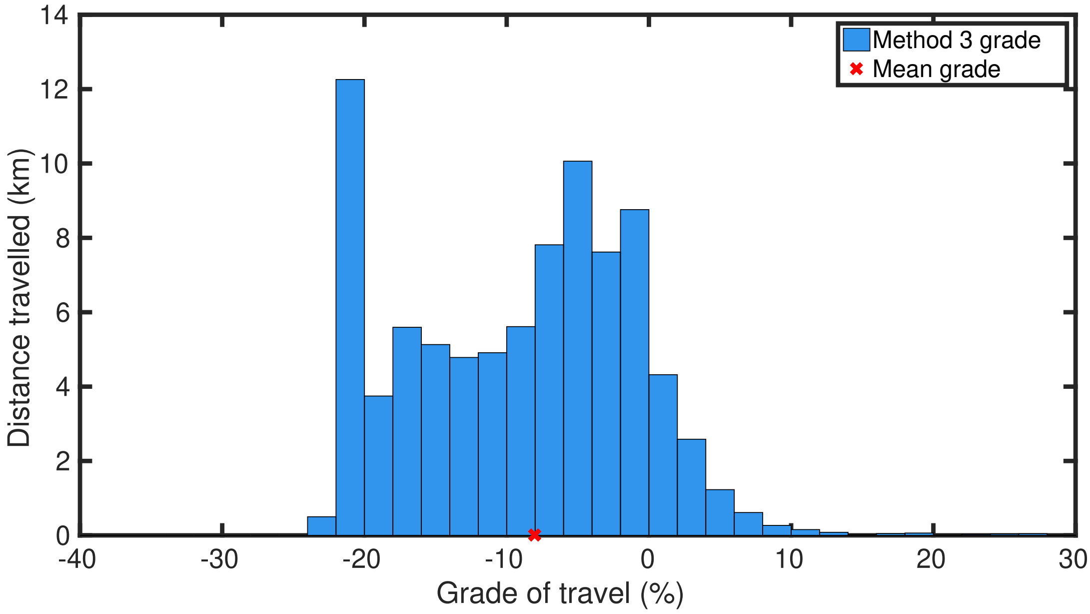


Figure D.18: Simulated travelling grades in zone 3.

Per-cycle volumes to prime

The following figures (D.19-D.24) compare the distribution of volume moved to prime per cycle for measured and simulated pivot push.

The volume moved by the simulated bulldozer is moderated by the pushable volumes component of the terrain simulation tool. Pushable volume is determined based on the grade of travel, and is constantly re-computed for changing grades. If an increase in grade is detected, the blade is slightly lifted to allow some material to remain, until the load within the blade has been reduced to the volume identified for the new grade.

The following observations are made;

- The simulation predicts a greater volume moved per cycle than was measured.
- The simulation consistently predicts a volume moved of of 37.5m^3. This is due to the pushable volumes model predicting the ideal blade volume for the large number of cycles which had a travelling grade of -25%.

Method 1

Figures D.19 and D.20 compare the volumes moved per cycle while completing Method 1.

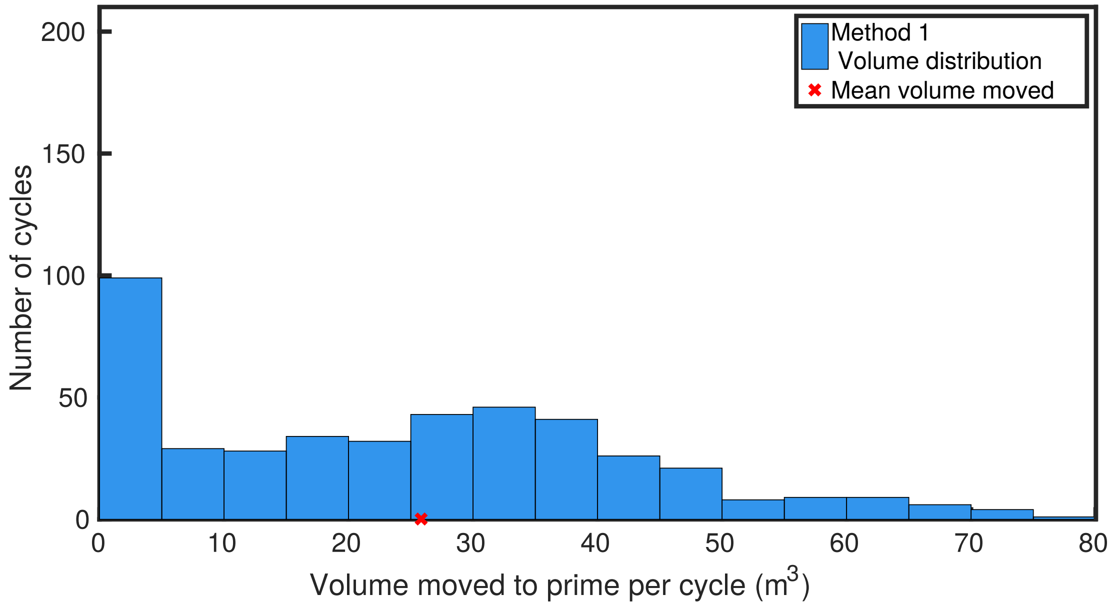


Figure D.19: Measured per-cycle volumes in zone 1.

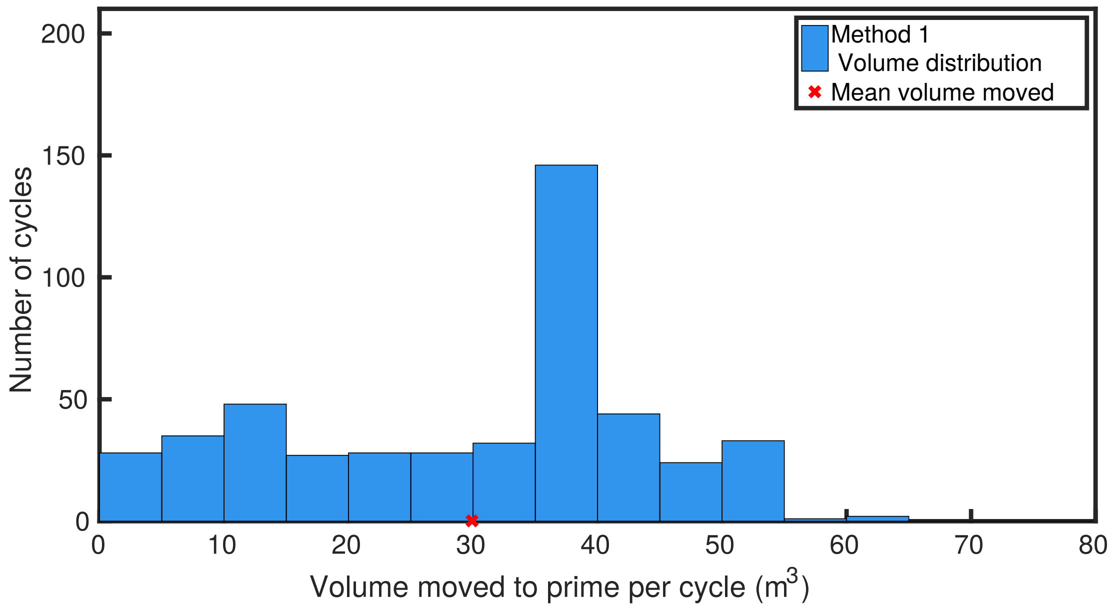


Figure D.20: Simulated per-cycle volumes in zone 1.

Method 2

Figures D.21 and D.22 compare the volumes moved per cycle while completing Method 2.

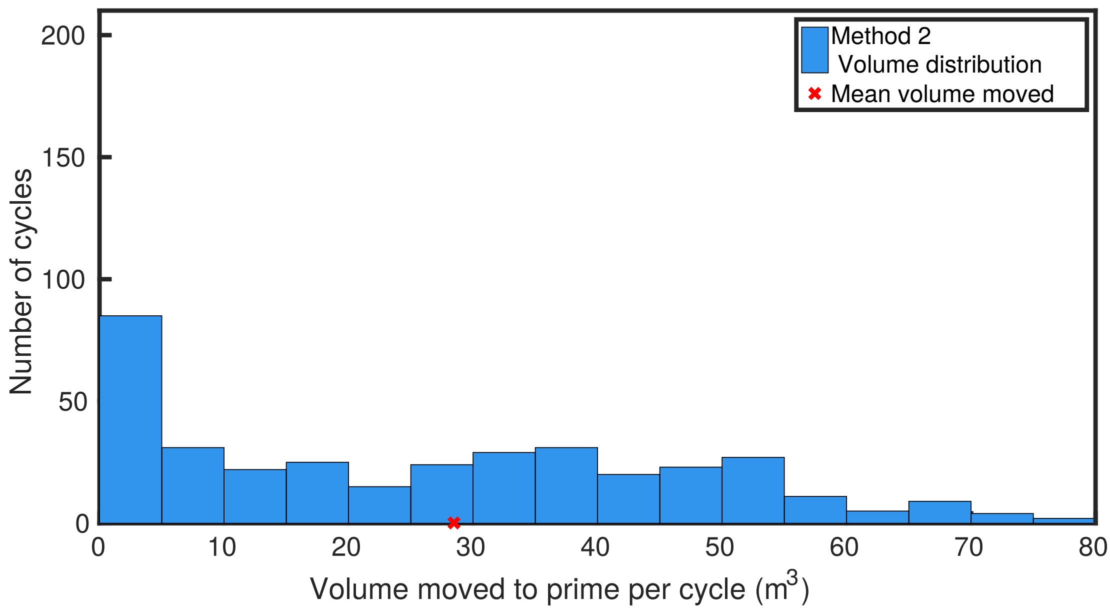


Figure D.21: Measured per-cycle volumes in zone 2.

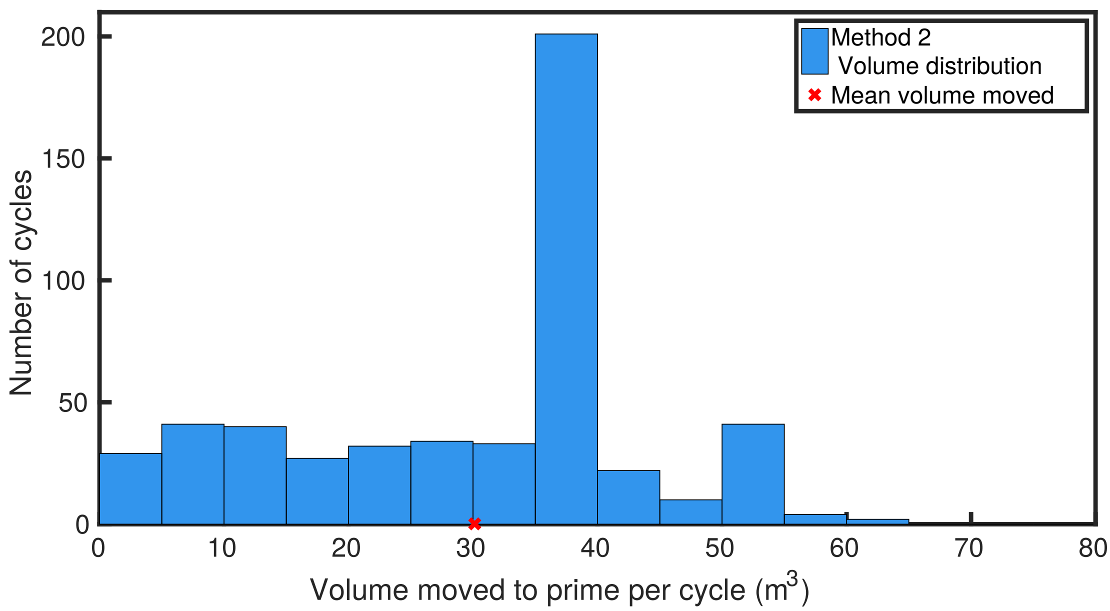


Figure D.22: Simulated per-cycle volumes in zone 2.

Method 3

Figures D.23 and D.24 compare the volumes moved per cycle while completing Method 3.

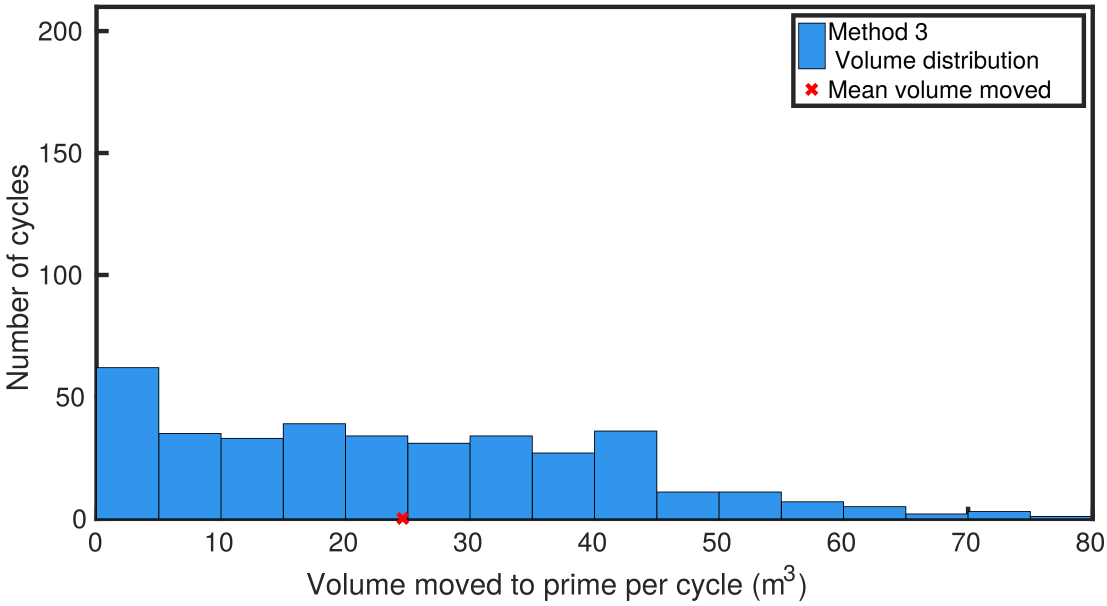


Figure D.23: Measured per-cycle volumes in zone 3.

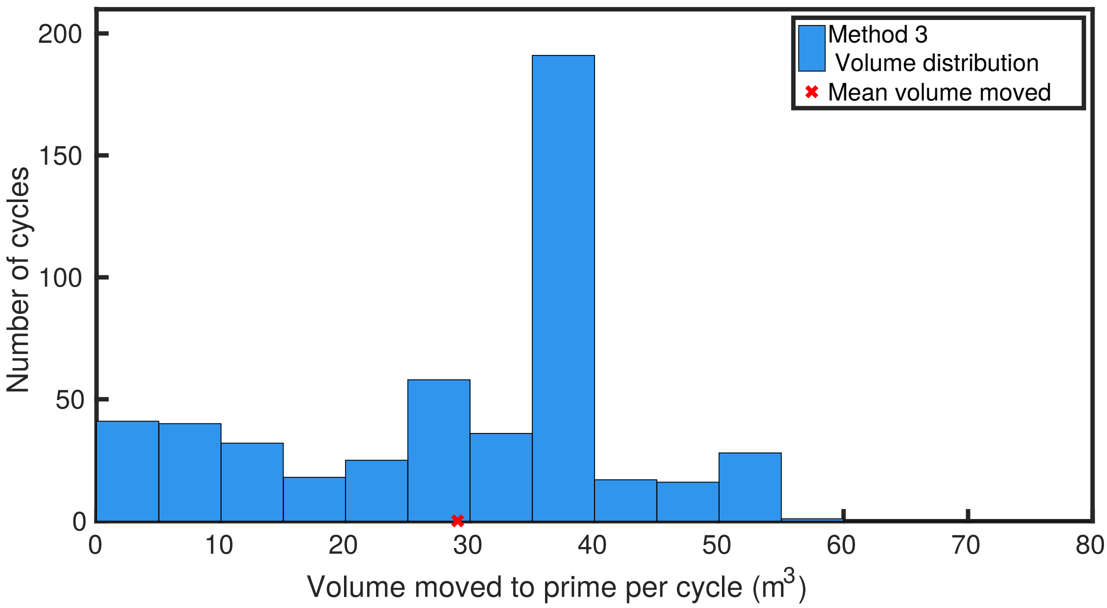


Figure D.24: Simulated per-cycle volumes in zone 3.

APPENDIX E

Additional analysis of the SATS trial

This appendix contains a range of additional analyses of the operations which were measured and simulated in the SATS trial. These analyses are used to support the arguments made in Chapter 4.

Cutting and dumping locations

E.1 Cutting and dumping locations

Manual zone

Figures E.1 and E.2 compare the progression of cutting and dumping locations between what was measured and simulated in the Manual zone.

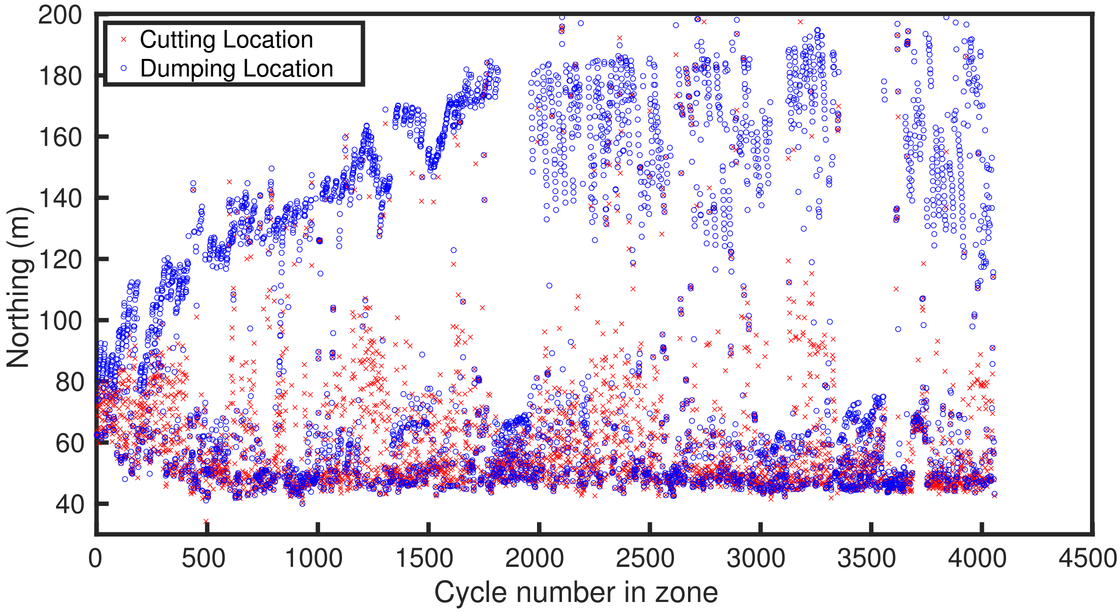


Figure E.1: Measured cutting and dumping locations in the manual zone.

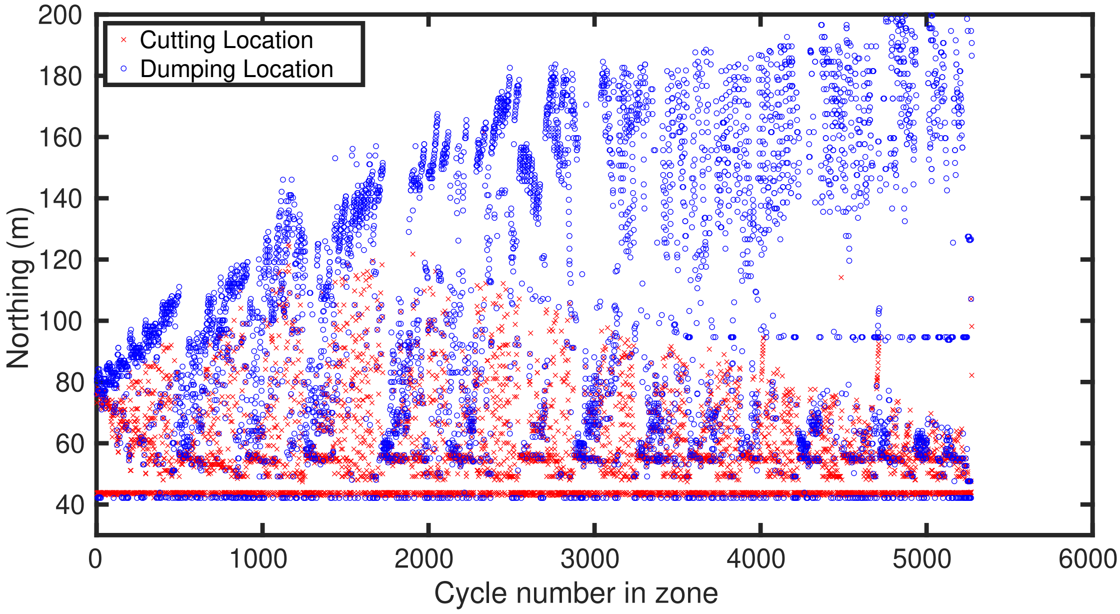


Figure E.2: Simulated cutting and dumping locations in the manual zone.

SATS zone

Figures E.3 and E.4 compare the progression of cutting and dumping locations between what was measured and simulated in the SATS zone.

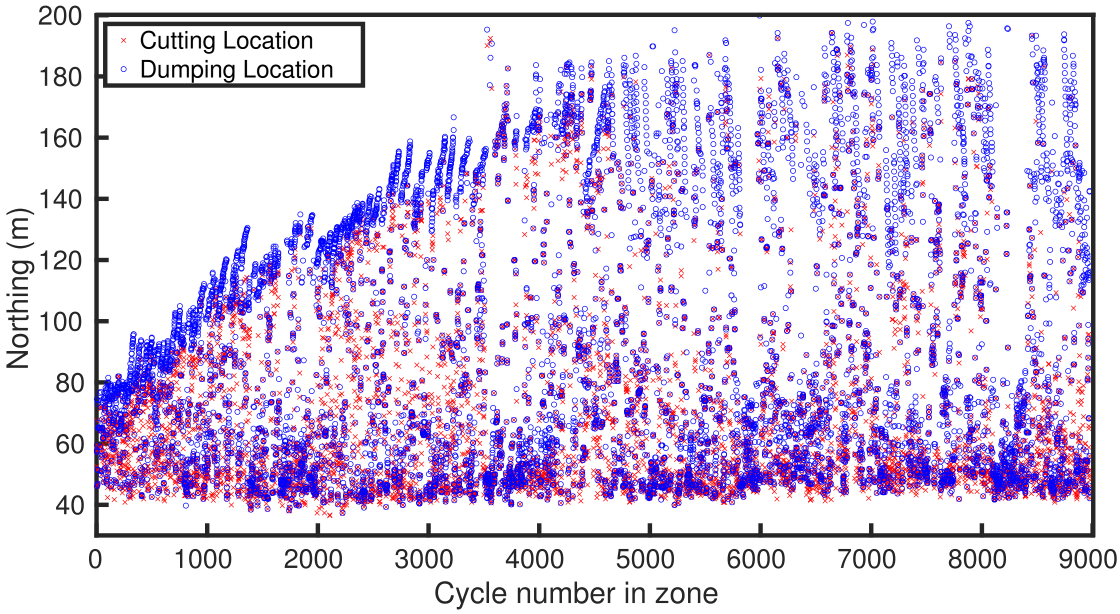


Figure E.3: Measured cutting and dumping locations in the SATS zone.

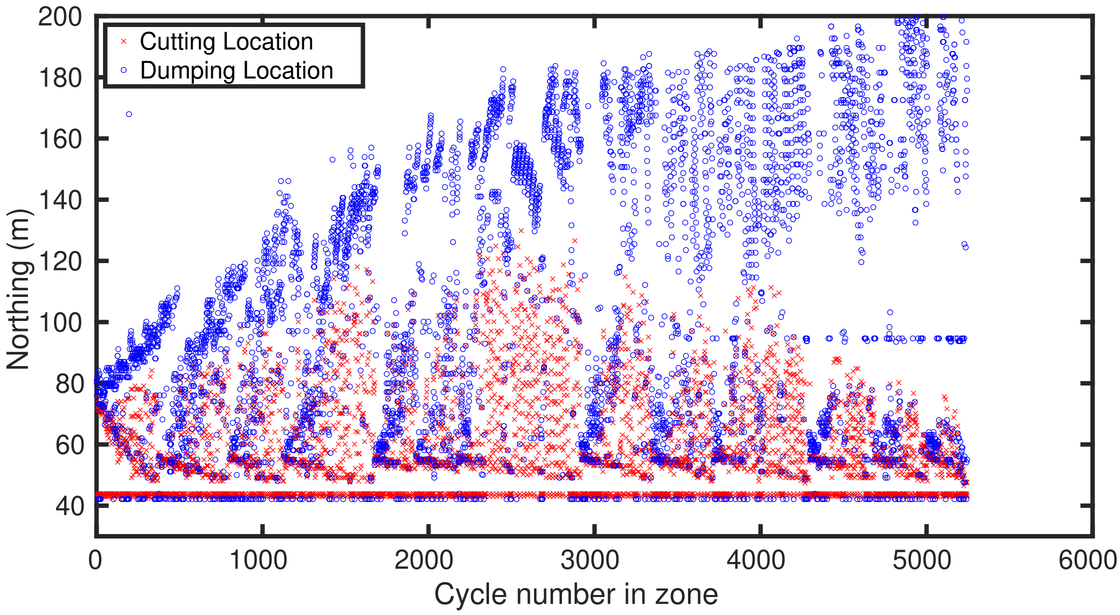


Figure E.4: Simulated cutting and dumping locations in the SATS zone.

Reversing velocity

Reversing gear locations

Figures E.5 to E.8 compare the patterns of reversing behaviour between manual and SATS operation. The y-ordinate represents distance into the slot travelling from the highwall to the low wall. The x-ordinate represents the number of reversing gear changes throughout the work in the zone. Coloured lines represent the reversing gear and grade of travel. Separate figures are shown for the dumping tactics of tipheading and backstacking.

It is found that manual operators reverse almost exclusively in second gear reverse (1R) and rarely change to second gear reverse (2R). SATS changes between 1R and 2R much more frequently, due to control logic specifying a minimum distance to be travelled in 1R before changing to 2R on each return pass.

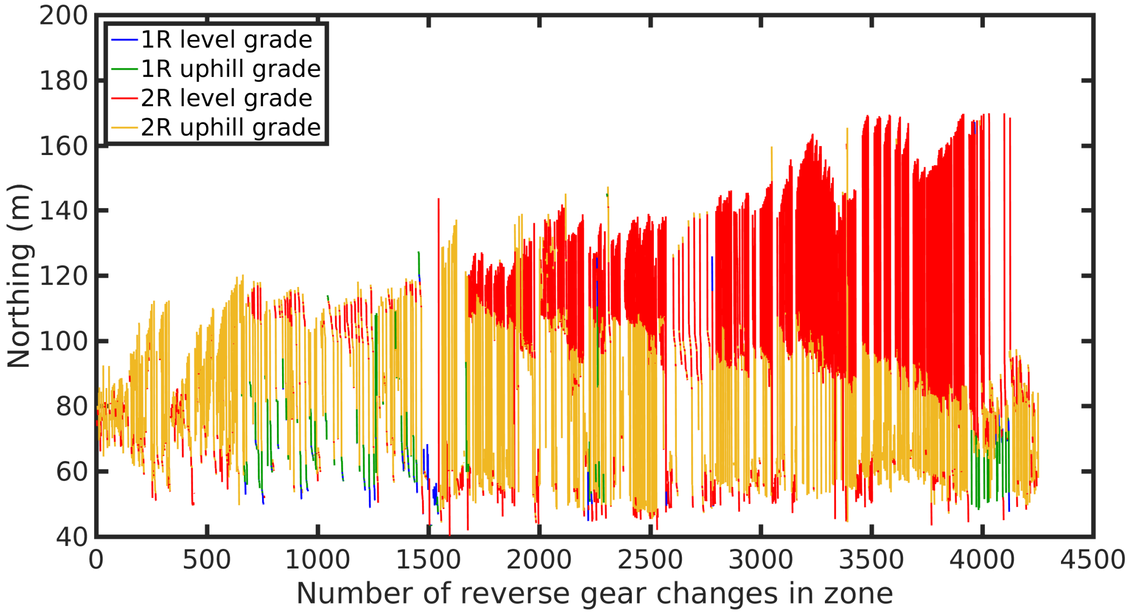


Figure E.5: Manual measured reverse locations while tip heading.

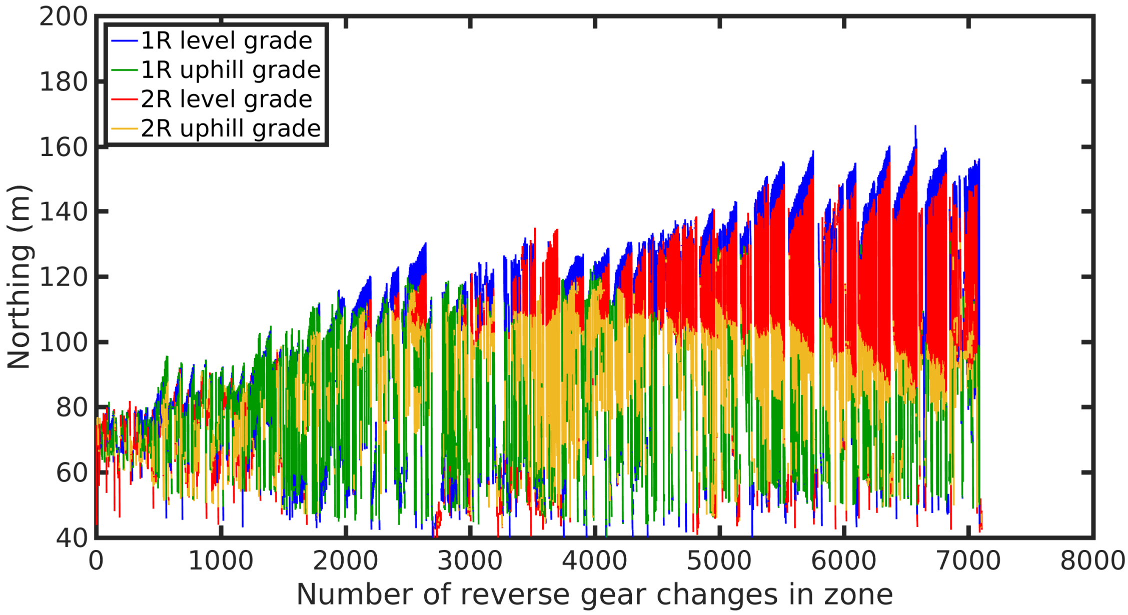


Figure E.6: SATS measured reverse locations while tip heading.

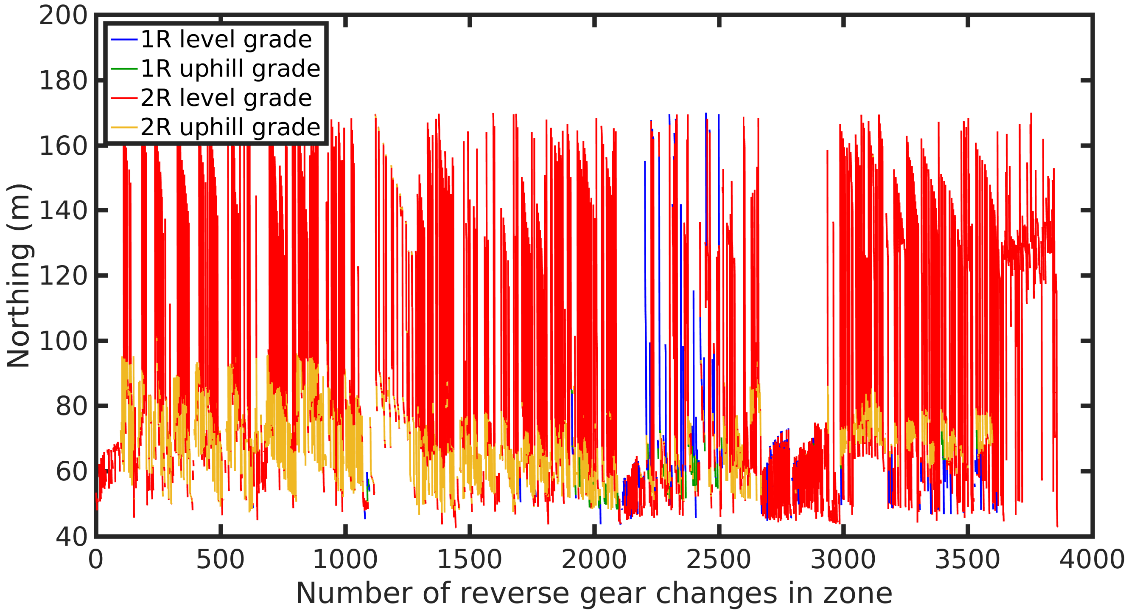


Figure E.7: Manual measured reverse locations while back stacking.

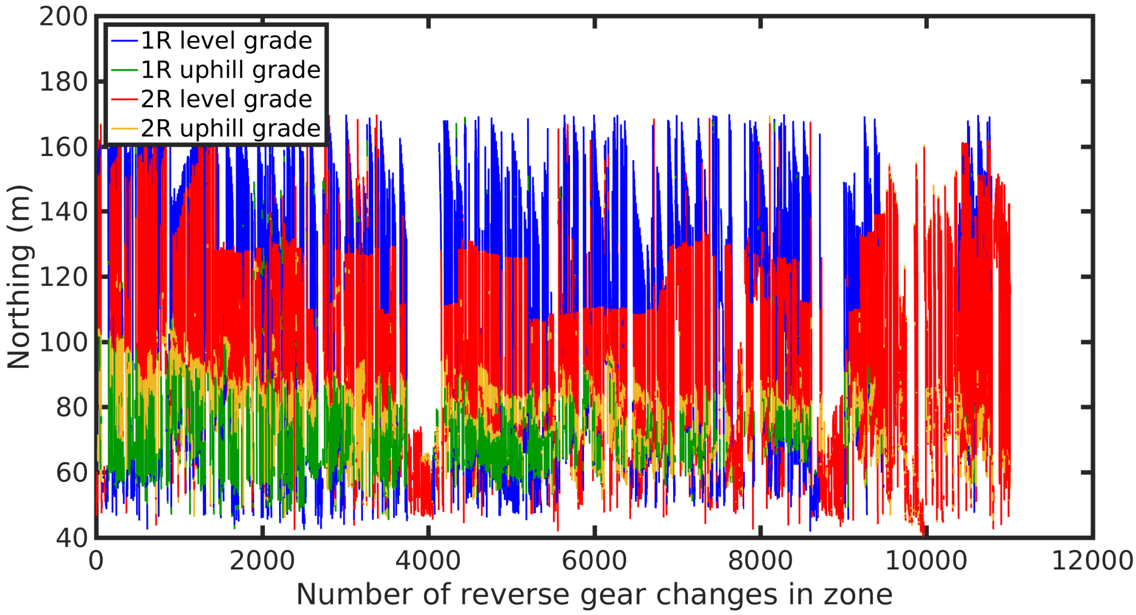


Figure E.8: SATS measured reverse locations while back stacking.

Reversing velocity distributions

Figures E.9 to E.12 show the relationship between engine speed and travelling velocity while reversing. The y-ordinate represents the engine speed in revolutions-per-minute. The x-ordinate represents the measured velocity of travel relative to the ground. The colour of markers represents the selected gear and travelling grade. Separate figures are shown for the dumping tactics of tipheading and back-stacking.

It is found that the velocity of travel is dependant on both the selected gear and the travelling grade. When in 2R, the travelling velocity is noticeably reduced when travelling uphill compared to travelling level. When in 1R, the velocity is less sensitive to travelling grade.

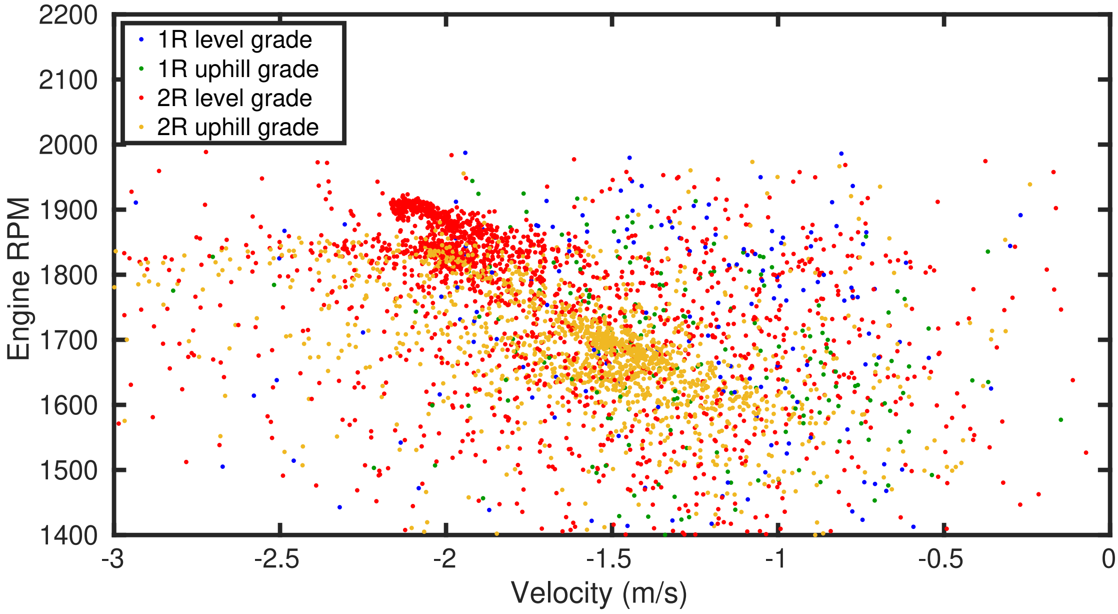


Figure E.9: Manual measured reverse velocities while tip heading.

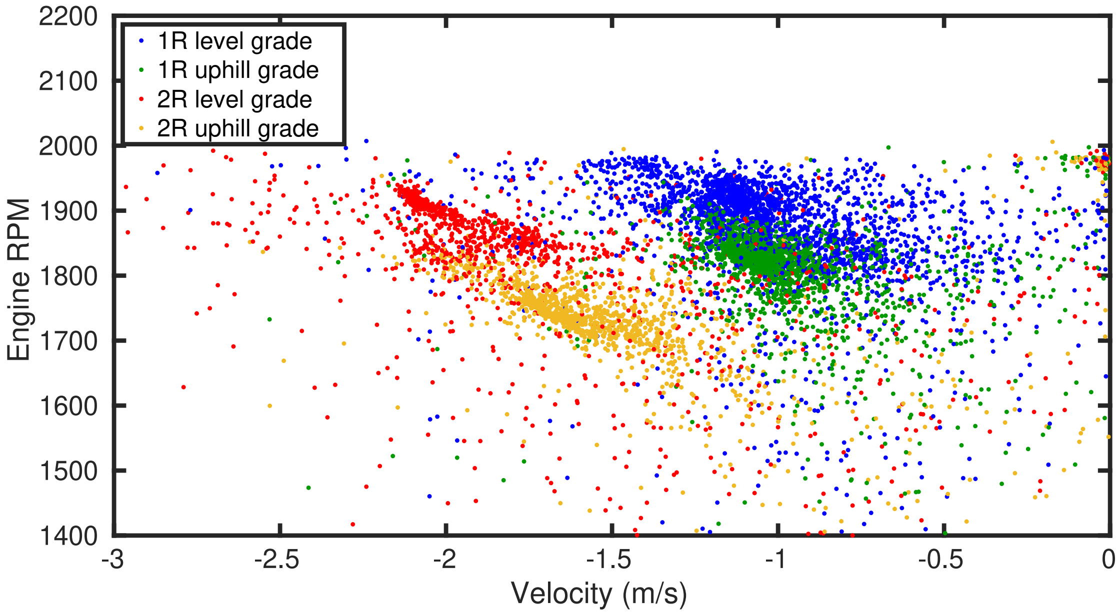


Figure E.10: SATS measured reverse velocities while tip heading.

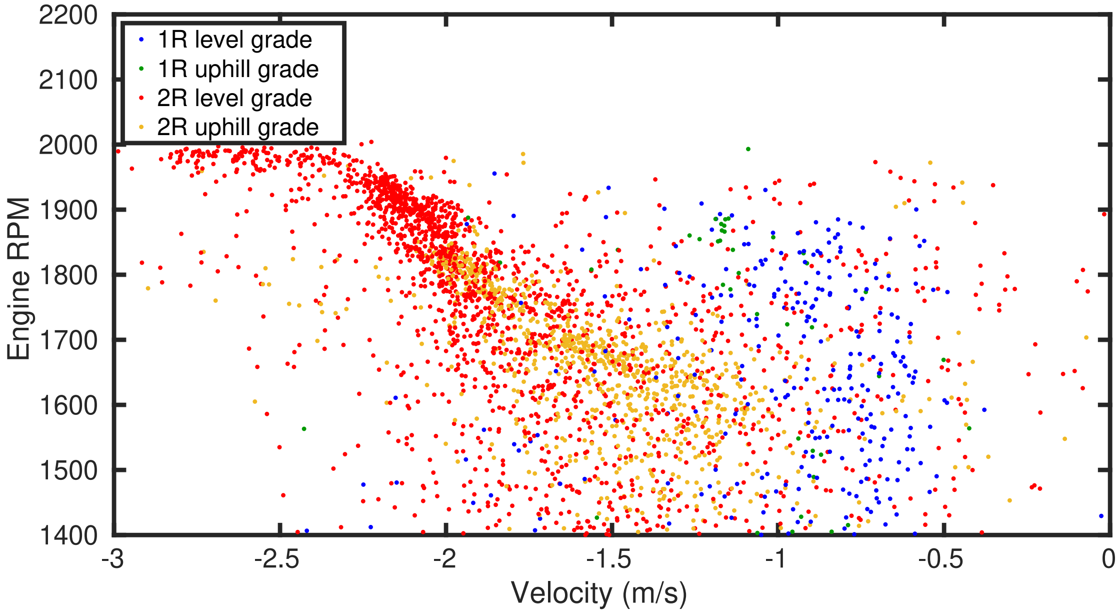


Figure E.11: Manual measured reverse velocities while back stacking.

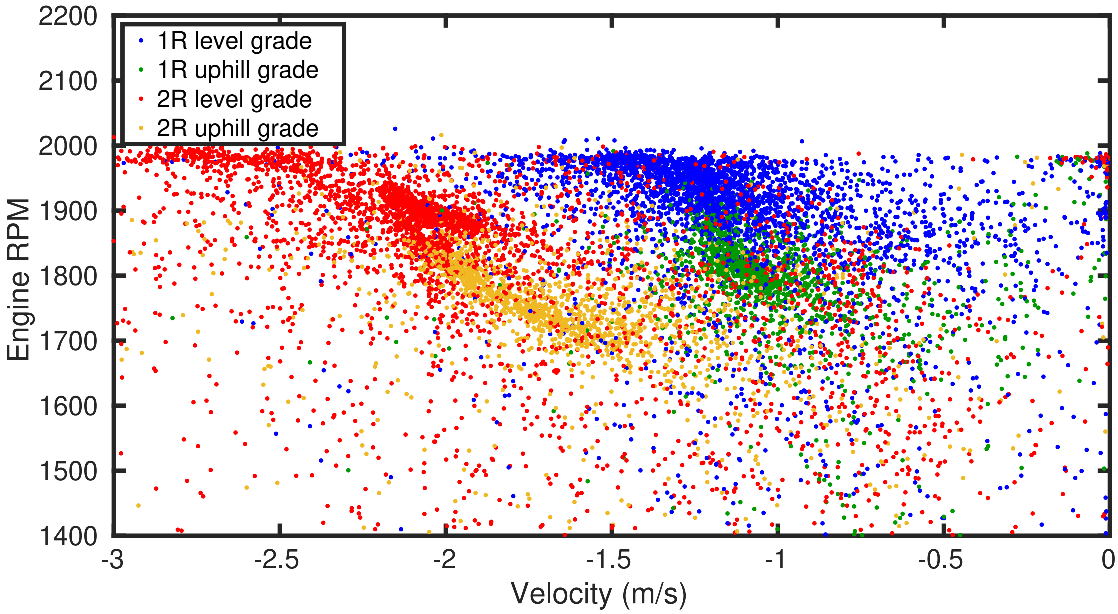


Figure E.12: SATS measured reverse velocities while back stacking.

Grade of travel

Manual zone

Figures E.13 and E.14 compare distributions of travelling grade between what was measured and simulated in the Manual zone. It is found that the distributions are not similar in shape, although the mean values are very close.

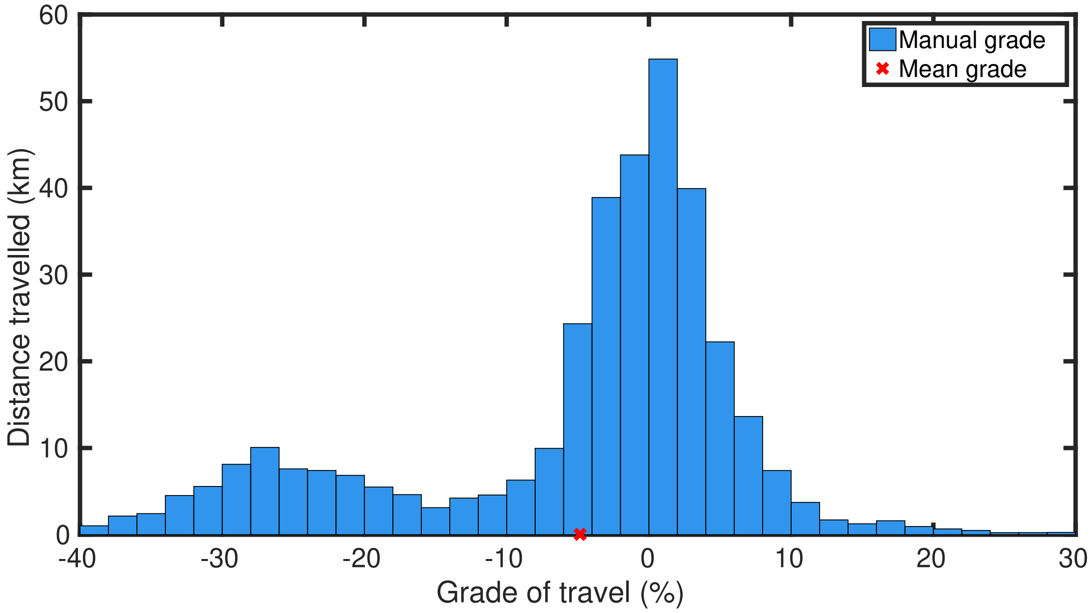


Figure E.13: Manual measured grade distribution.

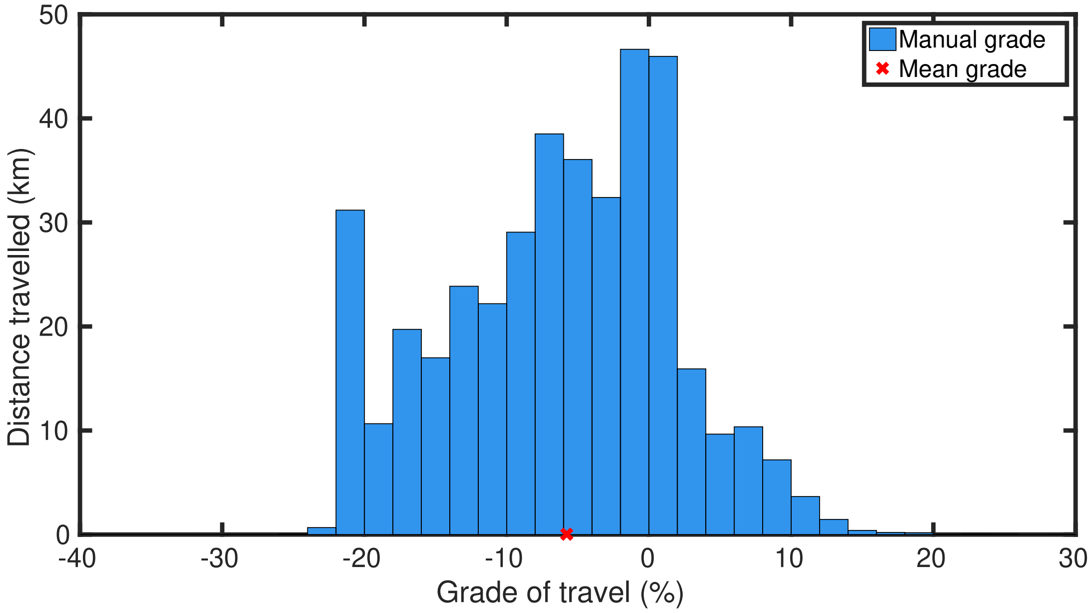


Figure E.14: Manual simulated grade distribution.

SATS zone

Figures E.15 and E.16 compare distributions of travelling grade between what was measured and simulated in the SATS zone.

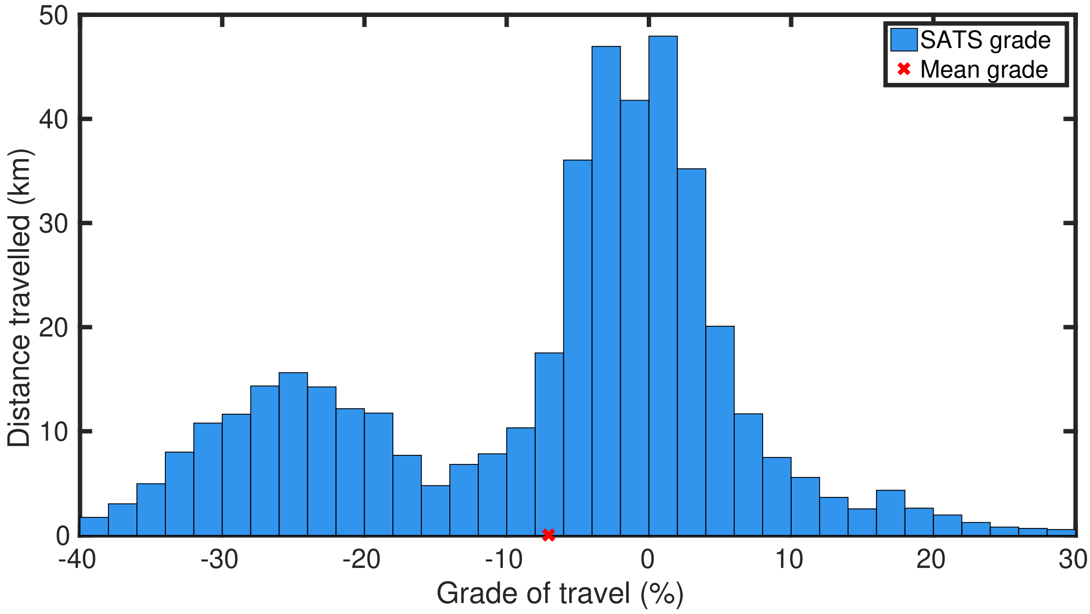


Figure E.15: SATS measured grade distribution.

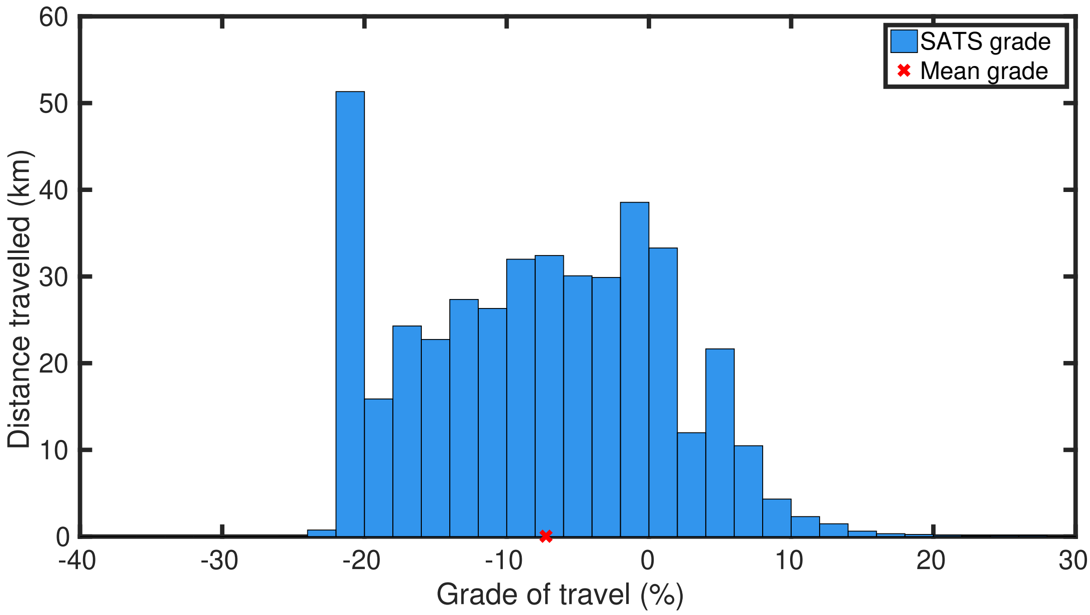


Figure E.16: SATS simulated grade distribution.

Volume moved per cycle

Manual zone

Figures E.17 and E.18 compare distributions of per-cycle volume moved between what was measured and simulated in the Manual zone.

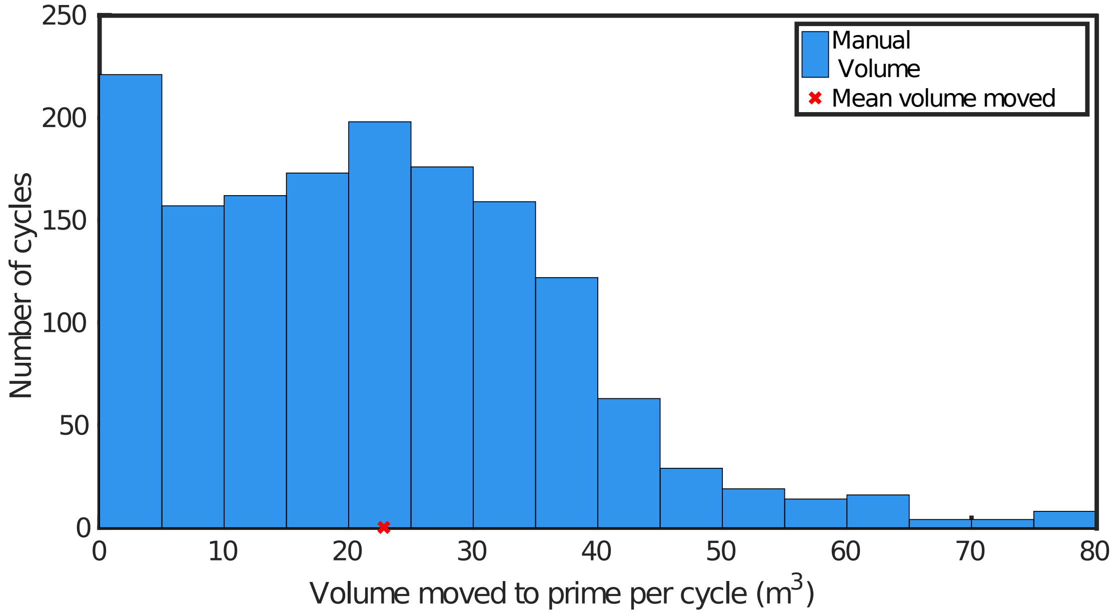


Figure E.17: Manual measured grade distribution.

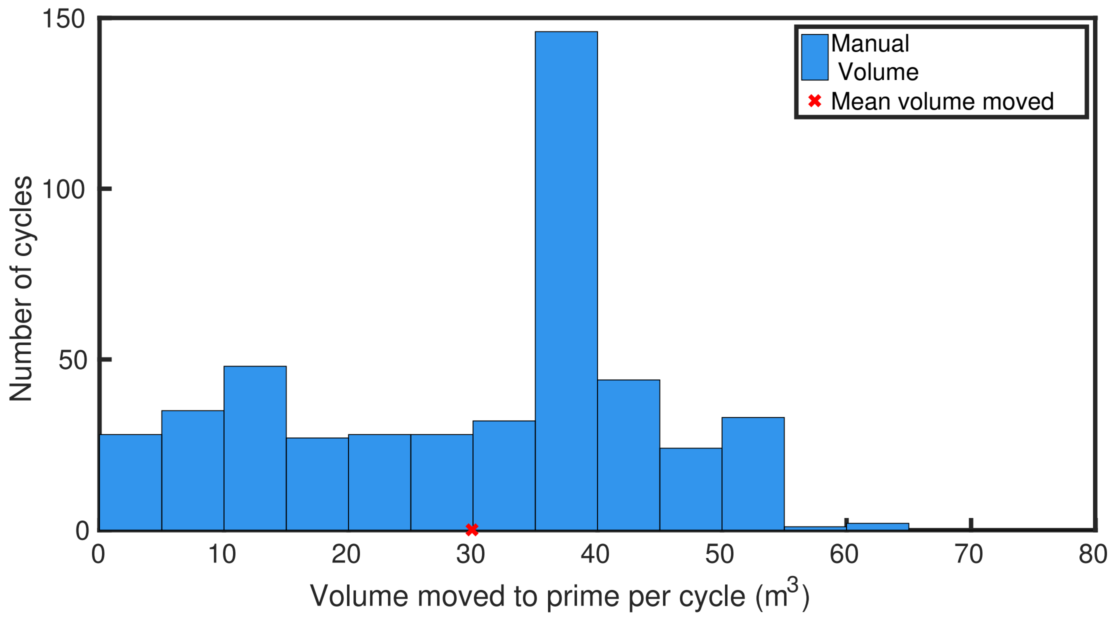


Figure E.18: Manual simulated grade distribution.

SATS zone

Figures E.19 and E.20 compare distributions of per-cycle volume moved between what was measured and simulated in the SATS zone.

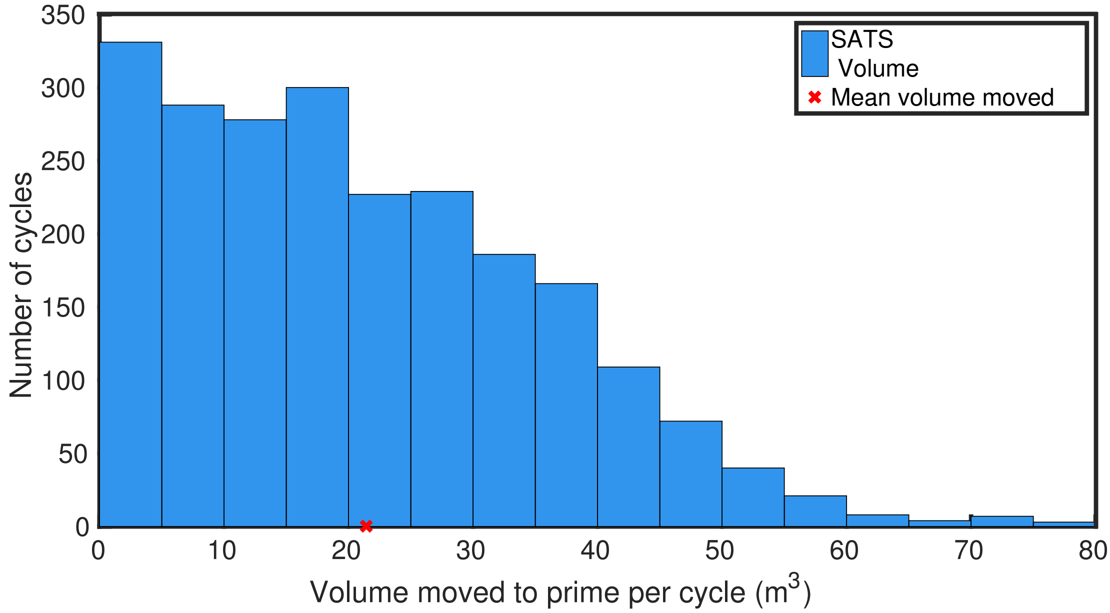


Figure E.19: SATS measured grade distribution.

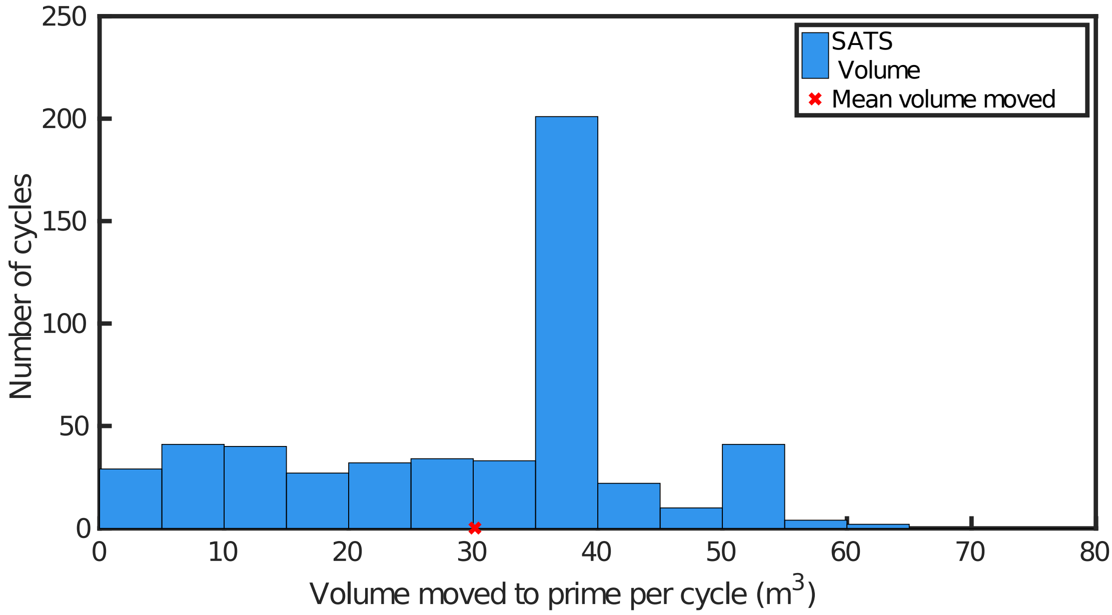


Figure E.20: SATS simulated grade distribution.